WHEN THE BLUE-GREEN WATERS TURN RED

Historical Flooding in Havasu Creek, Arizona

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 96—4059

Prepared in cooperation with the
BUREAU OF RECLAMATION

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Tucson, Arizona
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FRONTISPIECE.
A. Havasu Falls, showing normal spring flow in Havasu Creek (Melis, 1994).

FRONTISPIECE
B, Havasu Falls, showing a flash flood during the summer of 1970 (Billingsley).

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CONVERSION FACTORS

For readers who prefer to use inch-pound units, conversion factors for the terms in this report are listed below:

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.2818	foot (ft)
square meter (m^2)	10.76	square foot (ft^2)
cubic meter (m^3)	35.31	cubic foot (ft^3)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
hectare (ha)	2.47	acre (ac)
cubic meters per second per square kilometer ($m^3/s/km^2$)	91.49	cubic foot per second per square mile ($ft^3/s/mi^2$)

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called “Sea Level Datum of 1929.”

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By Theodore S. Melis, William M. Phillips, Robert H. Webb, and Donald J. Bills

Abstract

Havasu Creek, the second largest tributary of the Colorado River in Grand Canyon National Park, attracts numerous visitors each year owing to its spectacular scenery. Perennial streamflow seldom exceeds 2 cubic meters per second (m^3/s), but supports important stands of riparian vegetation, forms unique travertine pools, and spills over spectacular waterfalls. Havasu Canyon is home to the Havasupai Tribe, consisting of 423 members living in Supai, Arizona. Flooding in Havasu Creek poses a hazard to both visitors and residents of Supai. Frequent, large floods occurred in winter and summer during the late 19th and early 20th centuries; the largest occurred in January 1910. Smaller, summer floods occurred between 1935 and 1990. In September 1990, the largest flood in Havasu Creek since 1935, and possibly 1910, was generated by intense thunderstorms that lasted several days. The 1990 flood peaked at 575 m^3/s, caused severe damage to Supai, killed hundreds of ash trees (*Fraxinus* sp.), and altered travertine deposits in lower Havasu Canyon. Smaller floods in July 1992 and February 1993 also damaged Supai, eroded waterfalls, destroyed riparian vegetation, filled pools with gravel, and deposited coarse debris in the Colorado River. Most ash trees in Havasu Canyon germinated after 1940; peak recruitment occurred in the late 1960s and early 1970s, possibly in response to human disturbance. Nearly 80 percent of historical Havasu Creek floods have occurred during or immediately following El Niño years. Recent 1990s flooding reflects the flood regime of the first third of the 20th century, and frequency of intense daily precipitation at stations near Havasu Creek has followed patterns in recent flood frequency.

INTRODUCTION

Havasu Canyon, the second largest tributary of the Colorado River in Grand Canyon National Park, is one of the premier tourist attractions in the southwestern United States. The canyon contains superb scenery, including dazzling blue-green pools, waterfalls, and galleries of riparian trees that are considered a paradise to recreationists. The creek's flood plain is home to the Havasupai, the "people of the blue-green waters" (Breed, 1948; Iliff, 1954; Dobyns and Euler, 1971), who mostly live in and around the village of Supai (fig. 1). Havasu Canyon is also a place where large floods, including a devastating one in September 1990, periodically damage Supai and scour the creek channel of its plants and travertine deposits.

Because few streamflow data are available from its drainage basin, standard flood-frequency analysis cannot be applied to an assessment of flood hazards in Havasu Canyon. Anecdotal information on floods and their effects — particularly historical written and oral records, precipitation data, photographs, and the trees damaged or destroyed by floods — provide useful proxy flood data. Compilation of these data aids in placing the recent floods of Havasu Creek into an historical perspective, in addition to providing a baseline for future hydrologic studies. This investigation was undertaken in cooperation with the Bureau of

Reclamation's Glen Canyon Environmental Studies (GCES) program.

Physical Setting of Havasu Creek

Havasu Creek is the second largest tributary of the Colorado River in Grand Canyon, smaller only than the Little Colorado River (fig. 1a). The creek drains 7,822 km^2 of the Coconino Plateau along the south rim of western Grand Canyon; 541 km^2 of this area does not contribute runoff because of closed basins with internal drainage. Cataract Creek (fig. 1b) is the largest tributary of Havasu Creek, draining much of the high-elevation, eastern part of the drainage basin. The drainage area of Havasu Creek extends southward from the Colorado River toward the southern edge of the Colorado Plateau. The headwaters of Havasu Creek are near Williams, Arizona (fig. 1a), and most of the drainage area has thin, poorly developed soils over limestone that support desert grasslands and upland pinyon-juniper woodlands.

Numerous small reservoirs and livestock tanks throughout the Havasu Creek drainage basin provide public and livestock water supplies. The town of Williams manages five reservoirs in the headwaters with a combined capacity of about 3.4 x 106 cubic meters (m^3). The largest tank in the drainage basin, which has a capacity of 90,000 - 100,000 m^3, is on Monument Creek (fig. 1b).

Runoff in the upper reaches of Havasu Creek flows northwest toward the Colorado River through a bedrock canyon about 900 m deep (fig. 1c). Havasu Creek is perennial about 19 km upstream from the Colorado River; it is ephemeral upstream of Havasu Canyon, where the mainstem of the drainage is called Cataract Canyon. Perennial streamflow in Havasu Canyon results from springs in the Redwall Limestone that issue from the canyon floor. These springs are the main ground-water discharges from the "Coconino Trough" structural feature (Cooley, 1963). The aquifer feeding these springs is recharged regionally by an average precipitation of about 300 mm (Cooley, 1963).

Travertine features of the stream channel (for example, waterfalls and natural dams) continually change in form owing to flow in the creek and deposition of calcium carbonate ($CaCO_3$). Larger waterfalls, such as Havasu and Mooney Falls (fig. 1c), are relatively permanent features of Havasu Canyon and are controlled by the combination of Redwall Limestone and massive travertine deposits. The dams that create the pools and waterfalls of the canyon are initially formed by deposits of tufa, a soft form of $CaCO_3$ that continually precipitates from streamflow throughout the lower canyon. Tufa slowly recrystallizes to travertine, a more durable crystalline structure of $CaCO_3$. Remnants of ancient travertine examined throughout Havasu Canyon indicate that such features have characterized the creek's channel over the last several thousand years. Modern travertine is continually deposited in response to water chemistry and eroded by floods. Modern sites of travertine deposition occur mostly between Supai and the confluence of Havasu Creek and the Colorado River (Black, 1955; Giegengack and others, 1979).

Owing to floods and rarer debris flows, Havasu Creek periodically delivers coarse sediment to the Colorado River. Deposition of coarse sediment has resulted in the formation and persistence of Havasu Creek Rapid (fig. 1c), a moderately large rapid on the Colorado River (Stevens, 1990). Rapids in coarse-grained sediment are expected to be eroded during Colorado River floods (Kieffer, 1985), such erosion means that rapids such as Havasu Creek Rapid are expected to change size and shape in response to tributary sediment deliveries and Colorado River reworking (Melis and Webb, 1993).

Perceived at a larger scale, Havasu Creek is located in a region of the U.S. that is subject to climate forcing mechanisms manifested in the eastern Pacific Ocean. The Pacific Ocean temperature and atmospheric pressure anomaly known as El Niño and its counterpart, the Southern Oscillation (ENSO; see Diaz and Markgraf, 1992; Andrade and Sellers, 1988), have potentially significant effects on floods in Havasu Canyon. Onset of this anomaly phenomenon is recognized as a predictor of increased floods in southwestern North America, although no link has been previously made to floods in Havasu Canyon. However, relations between ENSO and streamflow in the southwestern United States (Kahya and

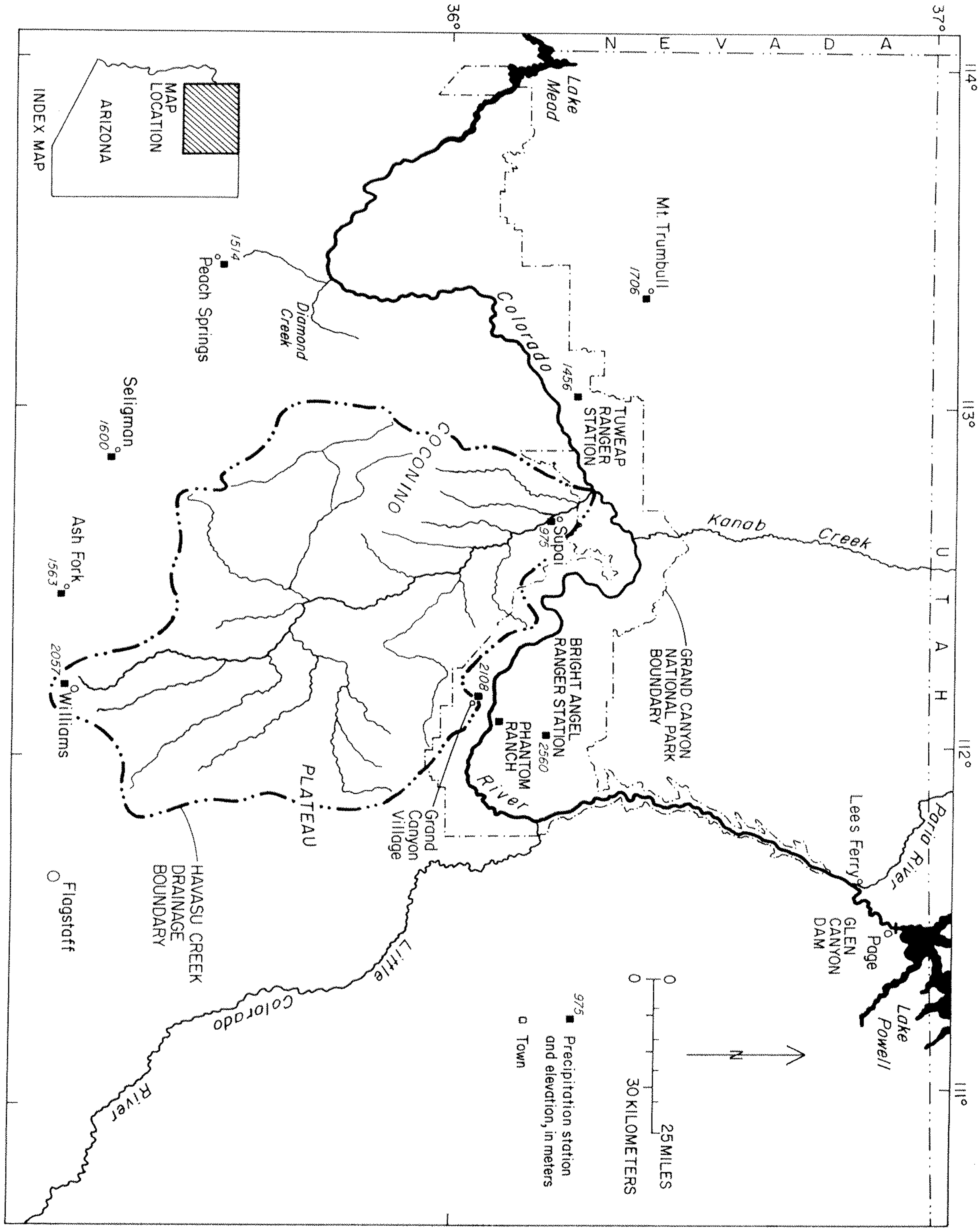
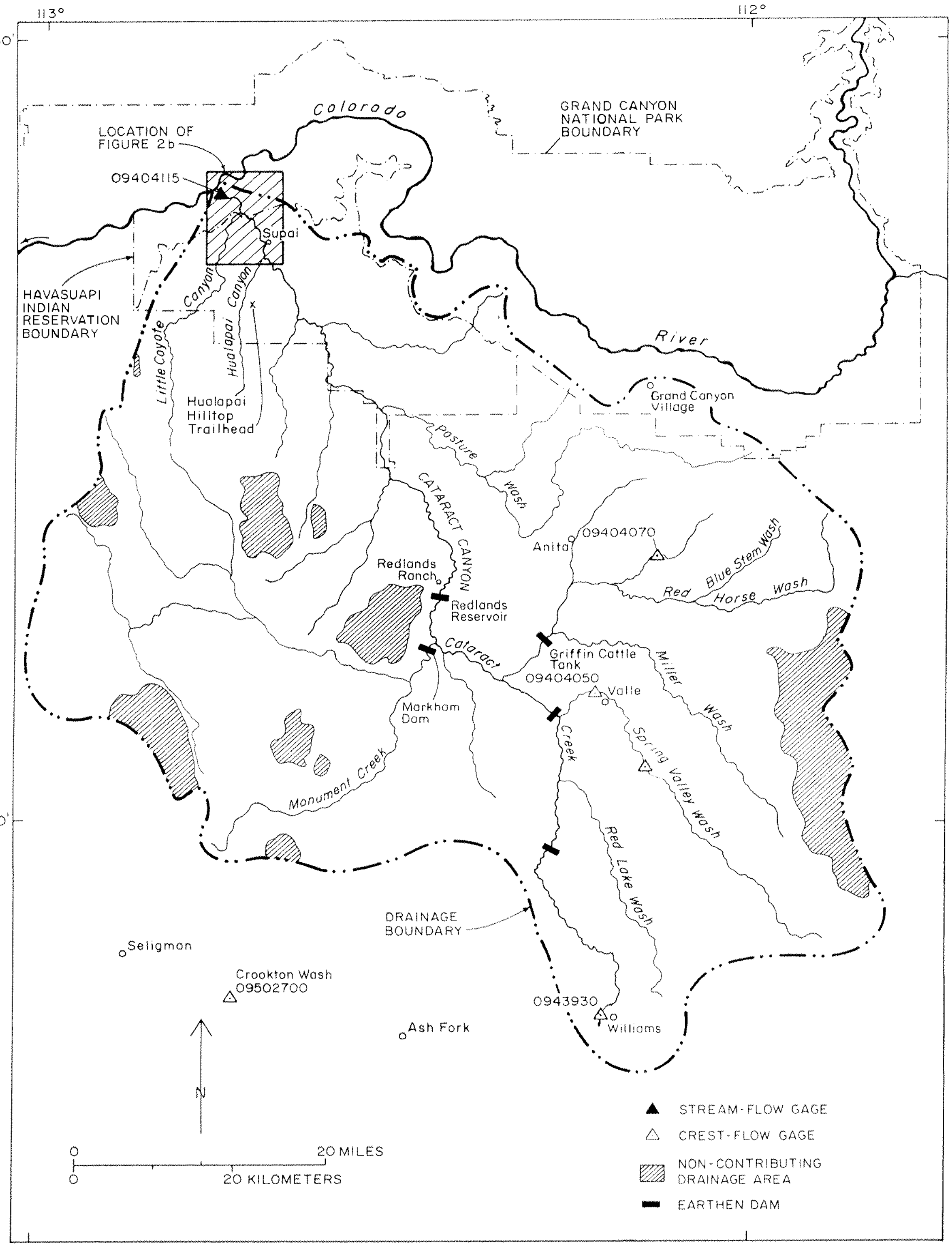
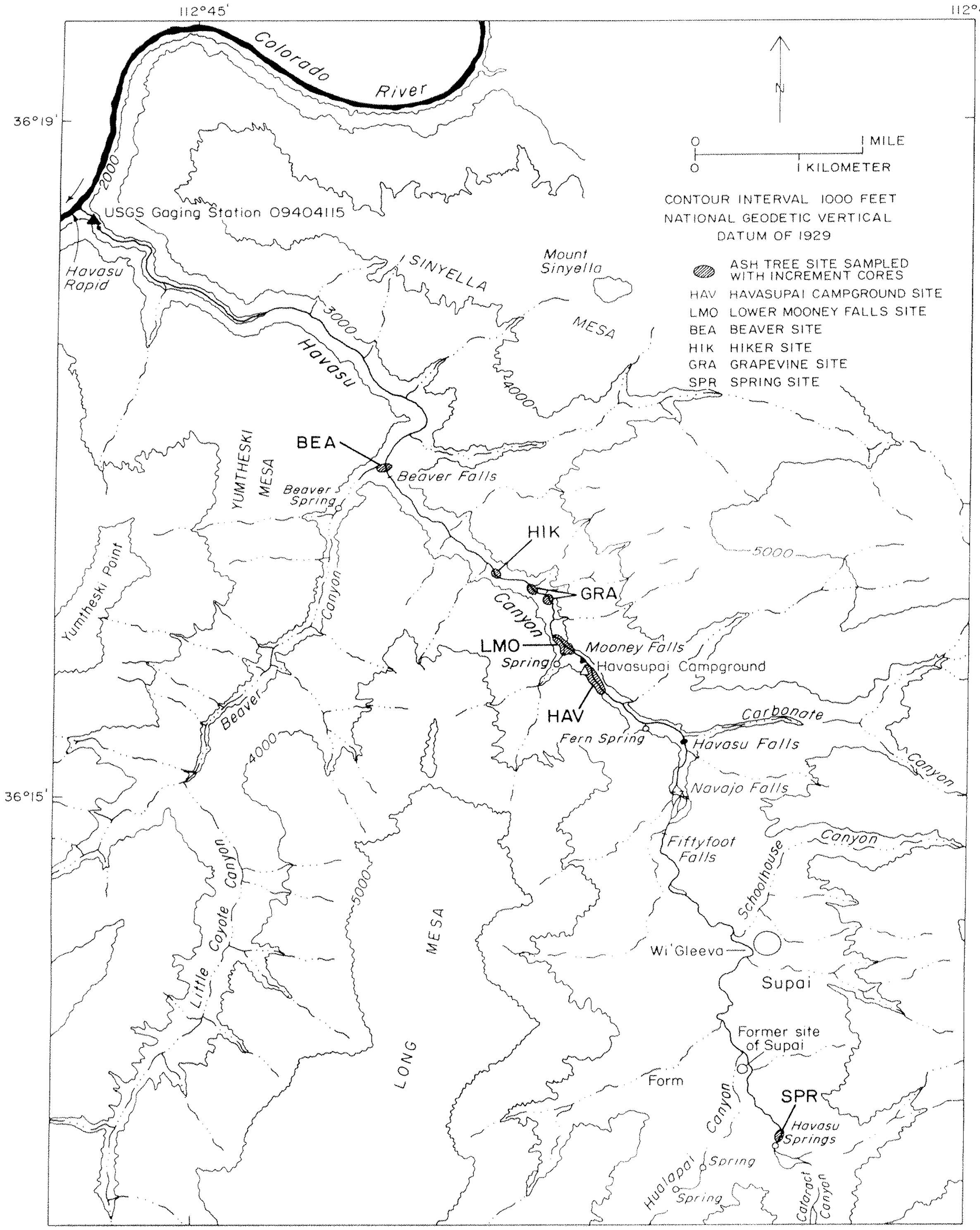


Figure 1. The Havasu Creek drainage basin and vicinity in northern Arizona. A, Locations of climatic stations in the vicinity of Havasu Creek.



B, The major tributaries to Havasu Creek.

Figure 1. Continued.



C, Havasu Canyon, showing the locations of dendrochronology sampling sites.

Figure 1. Continued.

Dracup, 1993; Cayan and Webb, 1992) indicate a positive correlation in other drainages in Arizona that are similar to Havasu Creek.

Recreation and Habitation Within Havasu Canyon

Because of its unique scenery, Havasu Canyon is a primary destination for many tourists visiting the Grand Canyon region. Havasu Canyon is accessible from the south rim and from its confluence with the Colorado River (fig. 1; Stevens, 1990). As a result of such ready access, the tributary's popularity as a backcountry destination has increased steadily since 1970. With increasing tourism in Arizona and the southwestern United States, demand for recreational use of Havasu Canyon will increase. Visitation of Havasu Canyon is presently limited by the Havasupai, but may follow the projected increases in Grand Canyon National Park visitation. Historically, visitation to the park increased from about 50,000 in 1920 to nearly 5 million in 1995. Park visitation is projected to approach 7 million by the year 2000, based on an average visitation growth rate of 5.5 percent per year from the 1960s through 1990 (Clark, 1994).

Whereas most tourists remain on the Grand Canyon's north and south rims, the popularity of backcountry recreation has steadily increased in the latter half of the 20th century. Narrow bedrock canyons provide a wilderness refuge for visitors from congested areas, such as Grand Canyon Village on the south rim (fig. 1a), but also serve as conduits for hazardous floods and debris flows (Webb and others, 1989). Recent research along the Colorado River has documented the frequency and magnitude of 20th-century floods and debris flows, generally termed "flash floods" (Webb and others, 1988; 1989; Melis and Webb, 1993; Melis and others, 1994). At least 90 debris flows have occurred in 169 of the 529 tributaries of Grand Canyon since about 1890 (Melis and others, 1994). The number of floods that have occurred in Grand Canyon tributaries is unknown, but is very likely far greater than the number of documented debris flows.

Because of the region's extreme relief, sparse vegetation, and dynamic weather patterns, floods in the Colorado River's tributaries typically occur with little warning. A 1984 debris flow in Diamond Creek is a good example of one form of geologic hazard in Grand Canyon. Diamond Creek, a large tributary of the Colorado River west of Havasu Canyon (fig. 1a), is a popular departure point for river trips. According to eyewitnesses, a wall of trees, boulders, and mud several meters high swept down Diamond Creek with no warning, carrying several large vehicles into the Colorado River (Ghiglieri, 1992; Webb, 1996). Remarkably, the debris flow caused no fatalities. Similar debris floods could occur in Havasu Canyon, particularly in tributaries such as Carbonate and Beaver Canyons (fig. 1c), but debris flows appear to be relatively rare in Havasu Canyon.

At least 10,000 tourists visit Havasu Canyon annually. According to the National Park Service (NPS), most river trips stop at Havasu Creek for several hours to hike and swim in the pools below Mooney Falls (fig. 1c; L. Jalbert, NPS, written commun., 1992). Because overnight camping is prohibited between Mooney Falls and the creek's confluence with the Colorado River, most Havasu Canyon visitation that originates from river trips occurs during the daylight hours of April through October. Appendix 1 shows recent visitation patterns of spring through autumn from the river to the lower reaches of Havasu Canyon downstream of Mooney Falls (L. Jalbert, written commun., 1992). These data, collected during a site-visitation monitoring program conducted by NPS, reflect only visitors that access Havasu Canyon from the Colorado River. Stevens (1990) reported that some 20,000 persons traveled the Colorado River through Grand Canyon via commercial and private river trips in 1990; many stopped to visit Havasu Canyon.

Backpackers hiking to Havasu Canyon from Hualapai Hilltop (fig. 1b) typically spend one or more nights in the Havasupai campground between Havasu and Mooney Falls (fig. 1c). The campground is on a low, flood-prone terrace adjacent to Havasu Creek. As visitation increases, so does the possibility of flood-related injuries and fatalities to tourists and the permanent residents, the Havasupai. The degree of flood hazard in Havasu Canyon depends on the amount of visitation, the variability of northern Arizona's climate, and changes in the population of Supai. Changes in

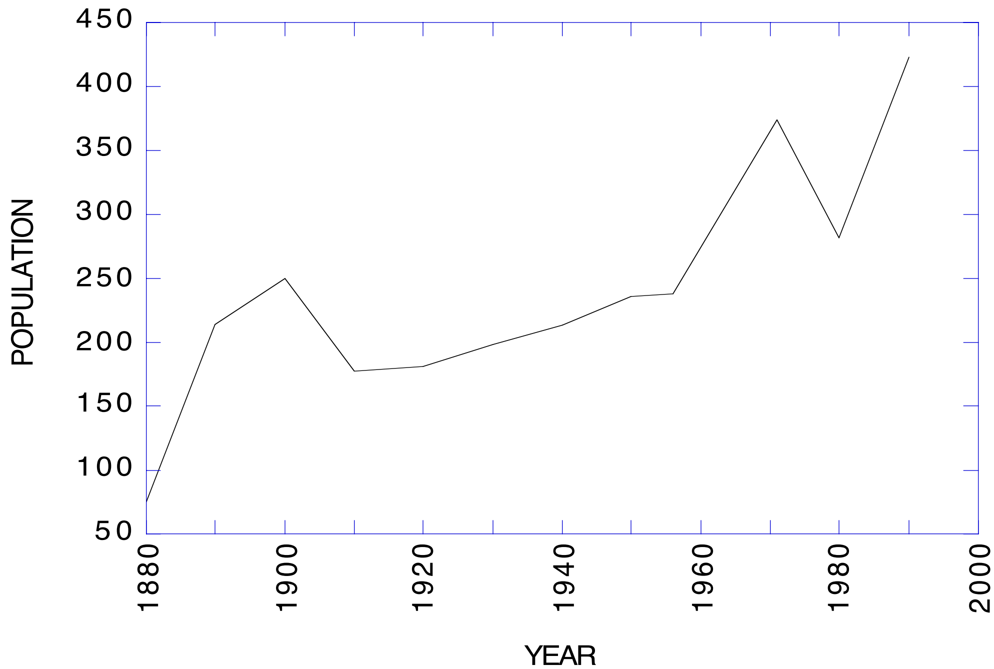


Figure 2. Population of Supai, Arizona, 1880-1990. The data are from the U.S. Bureau of Census.

habitation and tourism within the drainage basin, along with proposed changes in land use such as mining, may warrant further examination of recent floods and study of potential large floods in the future, to consider the possible development of an early warning system for flooding.

Even with adequate warning, Grand Canyon backcountry visitors and Supai residents have few escape routes from bedrock canyons during flash floods. Of the many tributaries in Grand Canyon, few are visited as much as Diamond Creek because of its ready access from the Colorado River. Havasu Canyon is probably second only to Diamond Creek in terms of annual visitation, but Havasu Creek has a larger and higher-elevation drainage area. Like most Grand Canyon tributaries, the flood history and geologic-hazard potential of Havasu Creek are poorly known owing to limited meteorologic and hydrologic data. Without sufficient historical data on floods, flood hazard and risk within the Havasu Creek drainage basin are difficult to assess.

Climatic fluctuations greatly complicate standard flood-prediction methods based solely on statistical approaches (Webb and Betancourt, 1992; also see Thomas and others, 1994, for a more detailed description). Webb and Betancourt (1992) suggested alternative approaches to estimating floods on the Santa Cruz River in southern Arizona, citing regional climatic variability as the primary reason. In a northern Arizona study relating regional climate to streamflow and sediment transport, Graf and others (1991) reported decadal-scale variability in suspended-sediment load, flood-plain alluviation, and flood frequency of the Paria River (fig. 1a) from 1923 through 1986. They attributed flood-frequency and sediment-flux trends mainly to low-frequency climatic variability. If climatic variability in Arizona has affected flood frequency in the Santa Cruz and Paria Rivers, then it is reasonable to conclude that flooding in Havasu Canyon may be influenced similarly. Webb and others (1991) arrived at a similar conclusion in a study of flood history in Kanab Creek, a Grand Canyon tributary that is near Havasu Creek and of similar size (fig. 1a).

Besides its status as a tourist attraction, Havasu Canyon is the heart of the Havasupai Indian Reservation (Hirst, 1976). In 1990 the Havasupai Tribe had 423 members, a number that has increased significantly since the 19th century (fig. 2). Most of the Havasupai live in 142 residential dwellings of Supai on the flood plain between Cataract Canyon and Fiftyfoot Falls (fig. 1c). Until

Table 1. Characteristics of selected precipitation stations and records in the vicinity of Havasu Creek

[All stations are in the state of Arizona]

Station[1] number	Location	Latitude-longitude	Elevation (m)	Distance to Supai (km)	Years of record used	Percent of record missing
0482	Ashfork	35°18´ 112°29´	1,618	114	1913-1995	11.5
1001	Bright Angel Ranger Station	36°12´ 112°04´	2,726	57	1948-1995	21.9
3591	Grand Canyon	36°03´ 112°08´	2,099	53	1904-1995	6.7
5744	Mt. Trumbull	36°25´ 113°21´	1,706	60	1920-1977	12.0
6471	Phantom Ranch	36°06´ 112°06´	834	55	1966-1995	0.0
7716	Seligman	35°19´ 112°53´	1,600	103	1905-1995	10.1
8343	Supai	36°12´ 112°42´	975	0	1957-1987	4.2
8895	Tuweep Ranger Station	36°17´ 113°04´	1,551	34	1948-1985	8.5
9359	Williams	35°15´ 112°11´	2,057	118	1904-1995	5.4

[1] National Weather Service station number (c.f., Green and Sellers, 1964)

they were confined to their reservation within Havasu Canyon, the Havasupai spent winters on the open plateau lands above the canyon's rim. In summer, the Havasupai occupied the canyon, using its flood plain for agriculture and the creek's perennial flow for irrigation (Dobyns and Euler, 1971; Hirst, 1976). Seasonal migration was a normal part of the tribe's culture until the Havasupai were restricted to the canyon bottom by federally-imposed reservation boundaries. After 1882, Federal reservation policies restricted Havasupai habitation to an area of 1,238 ha within the canyon, although the restriction was not enforced until about the time of the creation of Grand Canyon National Park in 1919 (Hirst, 1976). In the 1970s, part of the Havasupai's ancestral plateau land was returned (Hirst, 1976).

The most destructive flood in Havasu Creek since at least the mid-19th century occurred on January 2, 1910. The 1910 flood destroyed most of Supai, sweeping nearly all buildings in the village downstream, and also destroyed a small silver-mining operation in the canyon (Hirst, 1976). More importantly, the flood eroded or buried farmland vital to the Havasupai. Fortunately, at the time of the 1910 flood most tribal members were wintering on the plateau above the canyons and only one fatality occurred. A newspaper account described the devastation caused by the 1910 flood:

> The destruction of the Supai village in Cataract canyon leaves the Supai homeless. When first reported it was supposed that several Indians had been drowned, but later they were found. The Platinum mining company buildings and works were also destroyed by the flood. Several dams and stock water tanks went out at the upper end of the canyon during the heavy rains New Year's day letting the water go down through the narrow channel in a great flood. The water was higher than has been known in the past fifty years. Luckily the main part of the population of the village had gone on one of their pilgrimages to the rim and but few were left in the canyon at the time of the disaster. It is very probable that the government will have to secure another location for these Indians. There are about 225 of the tribe left and it will be but a few years until the tribe is practically wiped out (*The Coconino Daily Sun*, January 14, 1910).

The annual migration to the plateau during the winter may have saved many lives in 1910. Today, although parts of their ancestral lands outside of Havasu Canyon have been returned, most of the Havasupai reside in Havasu Canyon year-round. Instead of the dire predictions for their future made following the 1910 flood, the size of the tribe has more than doubled since 1910 (fig. 2). Following the 1910 flood, Supai was relocated to a wider reach of the canyon downstream from its original site near the confluence of Cataract and Hualapai canyons (fig. 1c). In spite of relocation, a trend toward year-round habitation in Havasu Canyon, an increased population, and increased tourism suggest that the Havasupai and others are exposed to a greater risk from floods in the 1990s than previously existed.

Purpose and Scope

The purpose of this study is to investigate, compile, and interpret historical data on flooding in Havasu Creek. Compiled historical accounts of flooding in Havasu Creek were intended to identify relations between flood hazards and the social and natural resources of the drainage basin, increase the current knowledge of the spatial extent of climatic nonstationarity in northern Arizona, and show the need for quantitative climatic and streamflow data for the Havasu Creek drainage basin. Because flood hazard and risk are concepts dependent on population density and land use within a drainage basin, flood hazard in Havasu Canyon has probably increased during the 20th century owing to increased tourism and habitation. Flood potential is also influenced by short- and long-term climate changes. The 1910 flood was an extreme flood event in the historical record, and completely destroyed Supai. However, because few people occupied the canyon at the time, only one fatality resulted. The floods from 1990 through 1993 illustrate the potential for damage and hazard to humans from smaller magnitude flooding in Havasu Canyon, particularly with respect to the Havasupai. A 1910 magnitude flood would now likely result in a much larger disaster for the inhabitants of the canyon.

Sources of Information on Floods in Havasu Creek

Because of its remote location and difficult access, hydrologic data relevant to estimation of flood hazards in Havasu Canyon are sparse. Precipitation was measured at Supai from 1957 through 1986; longer precipitation records are available for nine other stations near Havasu Canyon (fig. 1a, table 1). Although these records may show regional trends in precipitation and reveal approximate precipitation amounts during regional storms, the amount of precipitation delivered in flood-producing thunderstorms is not well known for the Havasu Creek drainage basin.

Streamflow data before 1990 are sparse for Havasu Creek (see Garrett and Gellenbeck, 1989). Annual peak discharge was collected at crest-stage gaging stations at West Cataract Creek near Williams (gaging station 09403930), from 1964 through 1976; Spring Valley Wash near Williams (09404050) from 1963 through 1976; Little Red Horse Wash near Grand Canyon (09404070) from 1963 through 1976; and Crookton Wash near Seligman (09502700) from 1963 through 1980 (fig. 1b). In November 1990, the U.S. Geological

Survey (USGS) established a continuous-record streamflow gage at Havasu Creek above the mouth near Supai (gaging station 09404115; fig. 1b and 1c), which will be referred to in this report as the Havasu Creek gaging station. Typical baseflow in Havasu Creek ranges from 1.7 to 2.4 m^3/s with only minor daily and seasonal variations (Johnson and Sanderson, 1968).

The recurrence intervals of the three 1990s floods cannot be calculated using standard flood-frequency analysis. Estimates can be made from regional-regression analysis, but such estimates are subject to large error (Roeske, 1978; Thomas and others, 1994). The streamflow record at the Havasu Creek gaging station, which began in November 1990, will help in future analyses. The gaging station was installed to support research activities associated with GCES and acquired added significance following the 1990 flood, which caused extensive damage in Havasu Canyon.

Proxy data for historic floods in Havasu Creek were gathered from sources including reports, written and verbal accounts of flooding, photographs of Havasu Canyon, dendrochronology data (including flood scars) collected from riparian ash trees (*Fraxinus* sp.), and records of extreme precipitation events in the 20th century. A partial flood history of Havasu Creek for the period 1885 through 1990 was reconstructed from these sources and was used as a context for evaluating hydrologic data of 1990 through 1993.

Repeat photography which is used extensively in this study, has proved useful in other assessments of environmental change along the Colorado River (Turner and Karpiscak, 1980; Stephens and Shoemaker, 1987; Webb, 1987; Webb and others 1989; 1991; Melis and others, 1994; Webb, 1996) and on Kanab Creek (Webb and others, 1991). Eighty-two historical photographs (appendix 2) of Havasu Canyon were identified during this investigation, and developed into a database of historical accounts and photographs of Havasu Canyon that may benefit future flood-frequency studies in the Grand Canyon region.

Units and Place Names

In this report, the English-system units of "river mile" and "feet" for contours on location maps are used; metric units are used for all other measures, including elevations of precipitation stations shown on maps. Use of river mile to describe the locations of tributaries along the Colorado River has considerable historical precedent (Stevens, 1990) and is reproducible. Lees Ferry (fig. 1a) is designated as river mile 0.0, and river-mile designations for Colorado River tributaries are assigned with distance downstream from that point. Place names in Havasu Canyon are derived from 7.5-minute quadrangle maps, although some features, such as the "Big Kids Pool," are commonly used by Colorado River guides and NPS personnel.

Acknowledgments

The authors gratefully acknowledge the assistance of the following people and institutions during this study. Historical photographs and documents were obtained with the help of Heather Hatch, Archivist, Arizona Historical Society; Joseph Muench, Photographer, Santa Barbara, California; University of Arizona Special Collections Library; Karen Underhill and Diane Grua, Northern Arizona University Special Collections Library; the Huntington Library; Grand Canyon National Park Archives; the Museum of New Mexico; and the National Archives. Appendix 2 lists the historical photographs and the photographers. V.A.S. McCord, Laboratory of Tree-Ring Research, University of Arizona, helped with collection, sample preparation, and analysis of tree-ring specimens from Havasu Canyon. Don Watahamagee, Tribal Chairman (1991), Havasupai Tribe, graciously allowed access to Havasupai lands in 1991 during field work. Minnie Marshall, a Havasupai tribal member from Supai (account of the July 1935 flood), Gary Bolton, Dennis Silva, Tim Whitney, and Kenton Grua (all professional river guides on the Colorado River from 1970 through 1995), and George Billingsley provided accounts of flooding in Havasu Creek. In 1991, Tom Brownold replicated his 1988 photographs taken for a hiking guide to Havasu Canyon (Thybony, 1989). Chuck Sternberg provided the drafted illustrations, and Dominic Oldershaw produced the photographic prints shown in the report. Special thanks go to David L. Wegner and his staff at the Bureau of Reclamation's GCES office for his support of this project and the funding of the Havasu Creek gaging station. Thanks also goes to the river guides and staff at OARS Inc. of Flagstaff, Arizona for logistical support for part of this study. Richard Hereford, Larry Stevens, and Waite Osterkamp critically reviewed the manuscript.

METHODS

Collections of published and unpublished articles, reports, photographs, and other documents such as personal journals pertaining to historical floods in the Havasu Creek drainage basin were examined at the National Archives, the University of Arizona, Northern Arizona University, and the Arizona Historical Society. Many historical photographs of Havasu Canyon were taken to show its unique scenic qualities and attraction to recreationists (Breed, 1948). A total of 142 photographs, of which 82 were historical were identified that showed Havasu Canyon from 1885 through 1994. These photographs (appendix 2) were used to reconstruct the relative timing and effects of 19th- and 20th-century floods.

Interpretations made from photographs do not provide absolute or quantitative information about floods, but prolific growth of riparian vegetation and travertine deposition at waterfalls and in pools may correlate directly with periods of infrequent or high-magnitude floods. The photographic record reveals characteristic channel conditions at distinct times in Havasu Canyon from 1885 to 1995. The damage to pools and trees during the 1990s floods suggests that historical photographs should preserve a record of the damage that occurred during other historical floods. The most valuable photographs bracket large floods documented by eyewitness or newspaper accounts. Fifty historical photographs were matched in Havasu Canyon; another seven photographs of the confluence with the Colorado River were matched from 1991 through 1994. Changes between the dates of the original and replicate views were interpreted at the camera station; additional interpretive work was conducted during preparation of this report. In addition, 32 other photographs of the creek and its confluence with the Colorado River (appendix 2) were examined for channel change indicative of flooding.

Oral and written accounts of flooding contributed to our knowledge of historical flooding in Havasu Canyon. The earliest flood accounts consist mostly of damage reports submitted by Indian Service employees to the Commissioner of the Office of Indian Affairs; the best example of this documentation relates to the January 1910 flood. Arizona newspapers typically reported the effects of the largest floods on Supai. Accounts of flooding in the 1930s, 1970s and 1980s were obtained by interviewing members of the Havasupai Tribe, Colorado River professional guides and NPS rangers who worked in Havasu Canyon; only one written account of floods in Havasu Canyon for the period of 1935 to 1970 was found. This gap is partly explained by infrequent visitation to the canyon during those decades, but it may also reflect a lack of large floods during that period.

In addition to photographs and historical accounts, dendrochronology was used to evaluate the timing and effects of flooding. Tree-ring analysis is commonly used in flood-frequency evaluation (Sigafoos, 1964; Alestalo, 1971; Yanosky, 1983; Hupp, 1988). The goals of the tree-ring sampling and analysis were to gather botanical evidence for past floods and determine the age distribution of the ash-tree community in Havasu Canyon before the 1990 flood; in particular, evidence related to previous floods in the Havasu Canyon was also sought.

A total of 145 cross sections were collected from ash trees (*Fraxinus* sp.) killed by the 1990 flood in Havasu Creek; the cross sections were retrieved from November 1990 through April 1991. To supplement the cross-section data with samples from trees that survived the 1990 flood, increment cores from 57 ash trees growing along the lower reaches of Havasu Creek were collected in June 1991. The increment cores were collected as low as possible on trunks, usually 0.30 to 0.50 m above the ground, in order to obtain a better estimate of germination age of the tree; samples collected higher up on the trunk may underestimate the germination age of the tree by several years. Increment cores were obtained from six sites (fig. 1c; appendix 3). Most of the cores were collected along cross-stream transects to document the age

Table 2. Statistical characteristics of precipitation data from stations near Havasu Creek

[All stations are in Arizona. Percentages represent of the number of days with daily precipitation exceeding 25, 50, and 75 mm and do not include days for which data were missing]

Station name	Percent of days > 25 mm	Percent of days > 50 mm	Percent of days > 75 mm
Ashfork	0.662	0.063	0.012
Bright Angel Ranger Station	1.087	0.133	0.063
Grand Canyon	0.526	0.030	0.006
Mount Trumbull	0.500	0.020	0.000
Phantom Ranch	0.152	0.000	0.000
Seligman	0.503	0.035	0.003
Supai	0.177	0.009	0.000
Tuweep Ranger Station	0.445	0.053	0.015
Williams	1.177	0.143	0.013

structure of the reach. Other cores sampled old-appearing trees in an effort to assess the maximum age of velvet ash in Havasu Canyon. In one locality, increment cores were collected from sprouts and scars on a tipped tree trunk.

All radial sections and cores were prepared using standard dendrochronological techniques (Stokes and Smiley, 1968; Phipps, 1985). Ash is a ring-porous hardwood with readily distinguishable annual rings. The annual rings and pore structures are typically visible to the naked eye, particularly after sanding. Earlywood and latewood segments of annual rings are defined by color and the size and frequency of pore structures. Earlywood is typically light brown with large pores in irregular rows of three or four; latewood is medium brown with few, smaller pores. In some cases, annual ring boundaries are distinguished with difficulty owing to thin or poorly developed latewood. Uniformity of ring width around the circumference of the specimens varied widely; many samples possess grossly variable ring widths along different radii. This eccentric growth ring pattern owes possibly to the flood-induced tipping of trees.

All wood samples were examined for flood-scarred rings as described by Yanosky (1983). The reconstructed date of a flood can be determined within a few years of the actual flood date by examining the scars preserved within a tree's growth rings (Sigafoos, 1964). Flood-scarred growth rings occur when the tree's cambium, or active growth layer, is damaged by the impact of flood debris, such as floating logs. Other factors can create scars; for example, rockfalls, fires, or damage from human activities. Flood scars can be readily distinguished from other types of scars (Yanosky, 1983).

Sixteen cross sections had embedded scars, presumably from flood damage. The ages of the scars were estimated from ring counts (McCord, 1990). During field work in June 1991, abrasion scars and flood-training features, such as sprouts or tipped trees, were sampled along the lower reaches of the drainage basin. Several living ash trees between Supai and the Colorado River (fig. 1c) exhibited flood training and were sampled by increment borer. A list of the dendrochronology samples appears in appendix 3.

Characteristics of daily precipitation records and stations in or near the Havasu Creek drainage basin were examined (table 1), and these data were analyzed for trends. Monthly and daily precipitation totals associated with the timing of known floods were studied to determine the range of precipitation typically associated with 20th-century floods in Havasu Creek. The frequencies of daily precipitation >25, >50, and >75 millimeters (mm) were tabulated for stations in the vicinity of Havasu Creek drainage basin (table 2) to determine if trends of intense 20th-century precipitation could be identified. Trends in the frequency of precipitation >25 mm were tested statistically to determine significance and temporal relation to historical flooding in Havasu Canyon. The nonparametric Kendall Tau-b test was used (SAS, 1993; Gibbons, 1985; Conover, 1980) to identify statistically significant precipitation trends within the periods 1900-1929, 1930-1959, and 1960-1993. Kendall Tau-b (T) was chosen over the rank correlation coefficient (R) because T approaches normality more rapidly than R (Gibbons, 1985, p. 296). Hence, Kendall Tau-b provided an advantage when analyzing precipitation over the relatively short periods available (<35 years).

The largest daily precipitation amounts for nine climatic stations in the vicinity of Grand Canyon were ranked (appendix 4). A storm was defined as the total precipitation over consecutive days; "storms" in the Grand Canyon region can last as few as 2 days and as long as 2 weeks. The recurrence intervals of daily precipitation and storms were estimated (appendix 4) using a modified Gringorten plotting position (U.S. Water Resources Council, 1981):

$$p = ((m - 0.44)/(n + 0.12)) * d, \qquad (1)$$

where p = probability of the event, m = the ranking of the event (1= largest), n = the number of days in the record, and d = the number of days in the season. The recurrence interval, R (yrs), is

$$R = 1/P. \qquad (2)$$

HISTORICAL ACCOUNTS OF FLOODING

Few historical observations of Havasu Canyon were made before 1900. The Havasupai probably witnessed many large prehistoric floods, and some of those events are documented in their oral history and mythology (Smithson and Euler, 1994). The Havasupai stored a years supply of food in shelters well above Havasu Creek as a contingency against flood damage (Hirst, 1976). Written accounts began after establishment of the federal reservation system and its administering agencies. Most of the early accounts of flooding in Havasu Creek appear in reports submitted by Indian Service officials, usually superintendents or teachers who lived at Supai. Only general references to floods before 1899 were made in these reports.

19th-Century Flooding

H.P. Ewing (1899) wrote the earliest account of flooding in Havasu Creek. Ewing, a teacher of the Hualapai and Havasupai, reported in his 1899 annual report to the Indian Affairs Commissioner:

> The Havasupai have plodded along in the even tread of their uneventful existence, providing their own subsistence without aid from the Government, except in the case of the disastrous floods of last summer [1899], when their crops were nearly all washed away by a flood. It then became necessary to tide them over until a new crop could be raised. This was done and 25,000 pounds of flour and 4,000 pounds of beans were issued to them (Ewing, 1899, p. 156).

The Havasupai's self-sufficient lifestyle before the summer of 1899 suggests that floods had not disrupted the tribe since establishment of their reservation in 1882. It was not possible to determine the date or amount of precipitation that caused the flood of 1899, because of the lack of data (table 1). Other 19th-century flooding is briefly mentioned in the local press later that year:

> Sometime in the past a great flood in the canyon destroyed all their granaries and killed many of the tribe. The balance all but starved before another crop was produced, and since then a year's crop is always kept stored in caves, high up in the rock walls of the canyon (Arizona Graphic, October 7, 1899, p. 2)

Floods of 1904-1905

Not long after the 1899 event, flooding in Havasu Canyon was briefly described by A.W. Floren in his 1905 report to the Commissioner of the Office of Indian Affairs: "Owing to frequent destructive floods during the last fifteen months... the general condition of the Havasupai Indians is not what one would wish to see" (Floren, 1905, p. 163). Although Floren does not report the exact dates of the 1904-1905 floods, precipitation at Williams was high in both the summers and winters of 1904 and 1905 (Sellers and others, 1985). Precipitation at Williams was above average in several months that had large storms (fig. 3). The winter, spring, and fall of 1905 were especially wet, with above-normal precipitation from January

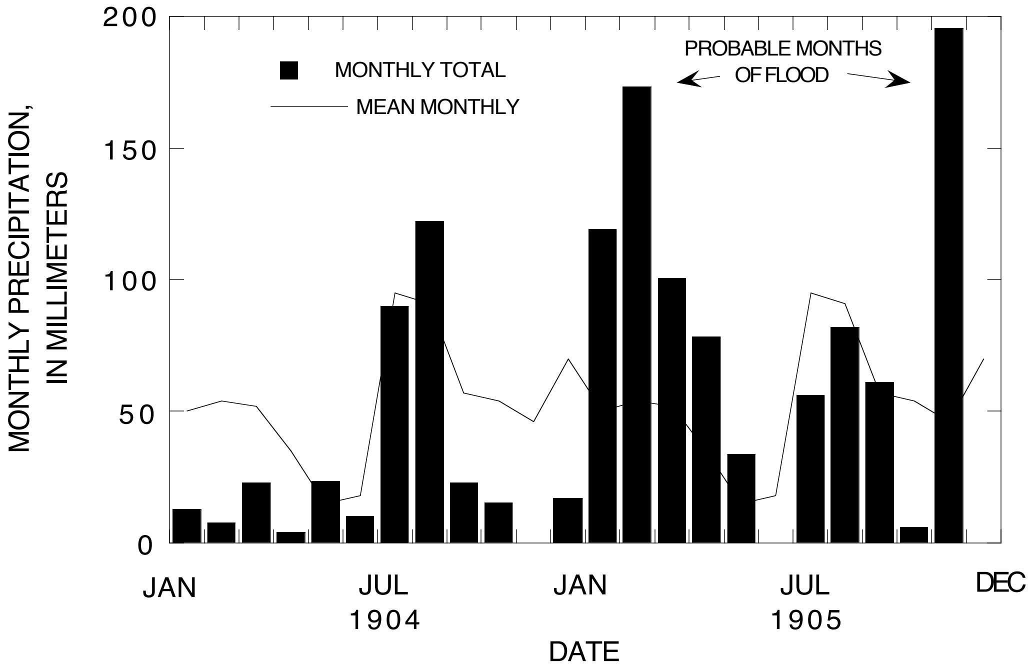


Figure 3. Precipitation at Williams associated with the 1904-1905 flood in Havasu Creek. The mean monthly values are from Sellers and others (1985) and the period of record is given in table 1.

through May and in November; floods occurred throughout Arizona, particularly in November (Sellers and others, 1985).

An unusually wet winter storm on November 26-28, 1905, dropped 97 mm of rain at Williams (Hansen and Shwarz, 1981); the storm has a recurrence interval of 4 years. The storm caused severe flooding throughout Arizona because warm rain fell on a thick snowpack (Sellers and others, 1985), resulting in larger runoff than would be expected from the storm alone. High precipitation at Williams during the summer of 1904 could have caused flooding (fig. 3); records for Grand Canyon, Seligman, and Williams show that August and September, 1905, had storms that also could have caused flooding. However, these storms are not equivalent in magnitude to the November 1905 storm, which is the most likely cause for a flood in Havasu Canyon.

The Flood of January 2, 1910

Havasu Creek had its most destructive historical flood on January 2, 1910. The flood was related to the combination of unusual weather conditions and land-use practices in the Havasu Creek drainage basin. On the basis of daily weather maps of the western United States, the storm that caused the 1910 flood was one of the most severe in Arizona during the 20th century. One report succinctly described the hydrometeorological conditions of the flood:

> Heavy snows fell on the upper watersheds of the Verde River and in the Bradshaw and San Francisco mountain ranges on December 20, 21, and 22, 1909, the snow remaining practically unmelted. On December 30 there was a marked increase in temperature, and like condition prevailed until January 1, 1910. The high temperatures and heavy rains in the northern portion of the Territory during December 31, 1909, and January 1, 1910, caused a rapid melting of the snow on the western and southern slopes of the San Francisco Range and in the Bradshaw Mountains, resulting in a very rapid run-off, which produced damaging floods in Cataract and Oak creeks, in Cataract Canyon adjoining the Grand Canyon, and in the upper Verde River (Brandenburg, 1910, p. 109).

Flooding was widespread in Arizona, as it was in November 1905 (Sellers and others, 1985). In January 1910, precipitation at Williams was higher than normal, whereas most of the rest of the year

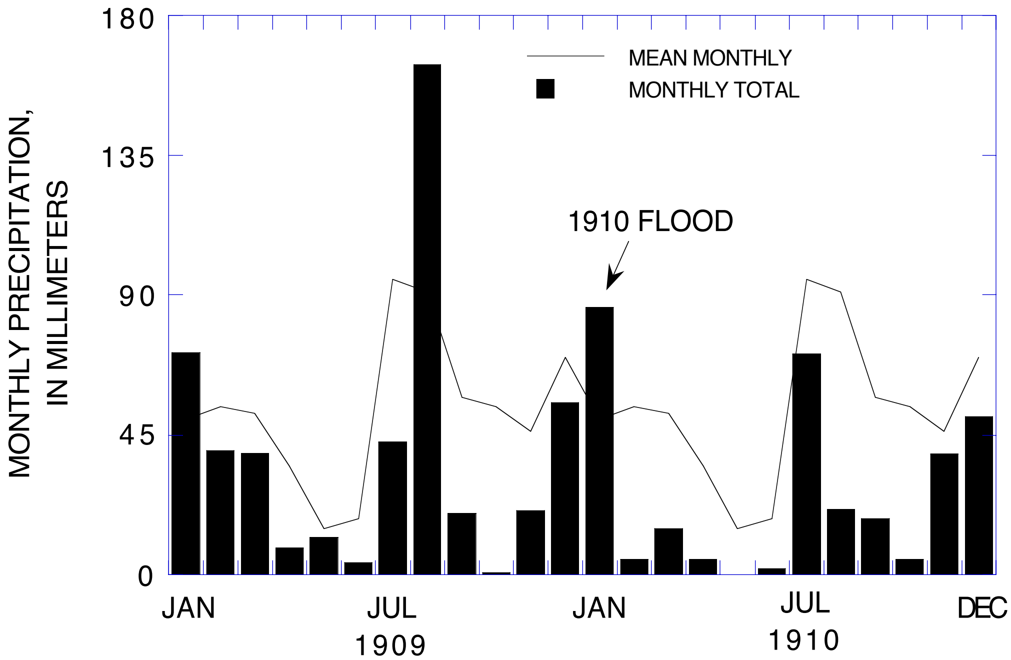


Figure 4. Precipitation at Williams associated with the January 1910 flood in Havasu Creek. The mean monthly values are from Sellers and others (1985) and the period of record is given in table 1.

was dry (fig. 4). A total of 56 mm of precipitation fell on January 1; this daily precipitation has only a 5-year recurrence interval, and the 4-day storm total of 75 mm (January 1-4) has a 3-year recurrence interval. These recurrence intervals for precipitation associated with such a flood are best explained by the facts that rain fell on snow in early January and that several earthen dams failed in the upper watershed.

The Indian Service superintendent to the Havasupai, Charles Coe, was stationed at Supai in 1910 and witnessed the flood. Coe reported the damage caused by the 1910 flood to the Commissioner of the Office of Indian Affairs, R.G. Valentine, in a telegram sent from Seligman on January 7, 1910:

> Sir: Confirming my telegram of yesterday, I have to report that the Havasupai agency and school were destroyed by flood waters January 2nd. The flood was caused by a warm rain suddenly melting the unusually heavy snow causing several large reservoirs in the Cataract drainage basin to give way. The water came down the canyon in a wall about 20 ft. [6.5 m] high, reaching the agency just before daylight. The employees all escaped with their lives after being in the icy waters about 4 hours. All the buildings and all records are a total loss. The property is all gone but 4 horses and a few things at the [Hualapai] Hilltop warehouse. I have heard of only [one] death, an old Indian woman, but fear that there may have been others as I was unable to communicate with all the Indians in the canyon. Fortunately nearly all or them had moved to the hills for the winter (National Archives Files, Washington D.C.).

Coe's description of the floodwater coming down the canyon "in a wall about 20-ft high," indicates that the flood probably covered the floor of the canyon from wall to wall. The flood was associated with the failure of at least four earthen dams in the headwaters of the drainage (Brandenburg, 1910) that were rebuilt after the flood.

The aftermath of the flood was also reported by Richard Barnes, a disbursement agent who was to become superintendent at Supai. Barnes, who arrived at the village around noon on January 2, found the village destroyed and Superintendent Coe, his wife, and another Indian Service employee trapped on top of one of only two structures remaining in Supai. The superintendent and the others had barely escaped by climbing onto the roof of their stone house as the floodwater raged down the canyon in the pre-dawn hours. In a letter dated January 14, 1910, Barnes describes the flood and its effects on the channel and flood plain of Havasu Creek:

> I arrived at Havasupai about noon of the second [January 1910]. The accident [flood] had happened a little before daylight of the same day. I found Supt. Coe, his wife, and the cook clad only in their night clothes and some blankets they had rescued from the flood. There was no shelter in the cañon and it was absolutely necessary that we get back to the warehouse at the cañon rim before night. The distance is over seven miles over a very tortuous trail, and so I had only about an hour to look around. Considerable of the farm land had been washed away, ditches were filled up or cut out, and fields covered with debris. Some few houses had been destroyed, though that is a loss that need not be taken very seriously as it is a matter of only a few hours work to build such a house as the Supais live in. From conversations that I had with Supt. Coe, and with various ones among the Indians, I gathered that no lives had been lost except one old Indian woman who was blind and feeble and so unable to help herself. About twenty horses were washed away. All food supplies, blankets, cooking utensils, etc. that were down in the valley were of course destroyed, but this does not cause as much destitution as might be imagined for the Indians store the bulk of their food in storehouses built into the cliffs, and all that was so stored was saved (National Archives Files, Washington D.C.).

The 1910 flood severely eroded the bottomlands of Havasu Canyon and buried many fields under sand, causing hardship to the inhabitants of Supai who depended on the land for agriculture. Channel incision by flooding made irrigating crops very difficult once fields and irrigation canals were restored. To reduce the likelihood of damage from future floods, Indian Service officials decided to rebuild Supai downstream in a wider part of the canyon below the confluence of Hualapai and Cataract Canyons (fig. 1c).

In late January, Barnes returned to Havasu Canyon to make an assessment of flood damage. In a letter to Commissioner Valentine dated January 28, 1910, Barnes described the channel and flood plain between Supai and Mooney Falls:

> The land in the upper part of the cañon has been cut out clear down to the gravel bed from one wall of the cañon to the other. All of the school land is gone and seven Indian farms immediately below it... The land that it left is in very bad shape. It is covered with debris, irrigating ditches are filled with sand, some fields have deep gullies plowed through them, others are covered with from six inches to two feet [0.2-0.6 m] of sand. The creek has divided and a part of it is running through some of the very best farming land. The channel of the creek has been cut out very much deeper, which will make it harder to get the water out on the land. The clearing off of the land and leveling it so that it can be irrigated, cleaning out ditches, turning the creek back into its proper channel, the building of a dam to raise the water, all means a great deal of work, and no time is to be lost if a crop is to be raised this year (National Archives Files, Washington D.C.).

Few other contemporary reports on the flood and destruction of the Havasupai village were made because of the remoteness of the canyon. E.L. Kolb, an early river runner and photographer of the Colorado River, wrote about the canyon's condition both up and downstream of Supai in 1911:

> A recent storm [1910] had remodelled all the falls in Cataract Creek of Havasu Canyon, cutting out the travertine in some places, piling it up in others. A great mass of cottonwood trees were also mixed with the debris. The village, too, had been washed away and was then being rebuilt. We had been told that the tunnel [leading down through Mooney Falls] was filled up, and as far as we knew no one had been to the [Colorado] river since the flood (Kolb, 1914, p. 246).

Kolb's description indicates that the 1910 flood had a significant impact on the riparian vegetation and geomorphology of the creek channel. Descriptions of the effect of the 1910 flood on Havasu Creek suggest that the flood, and the storm that caused it were much larger than any other in the 20th century. It is impossible to determine how

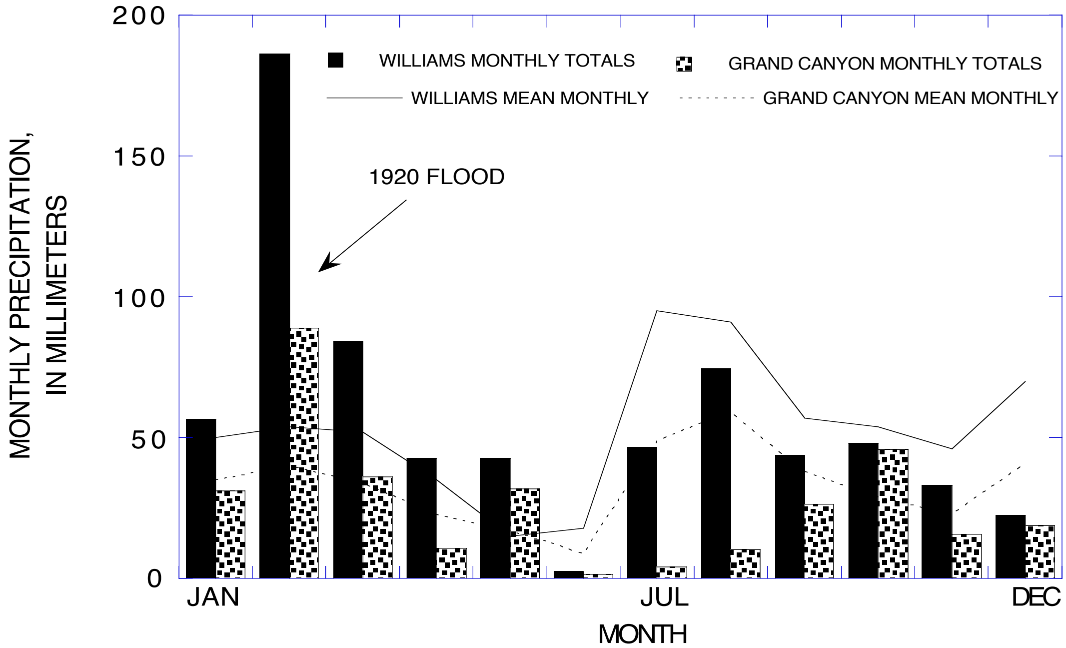


Figure 5. Precipitation at Williams and Grand Canyon associated with the February 1920 flood in Havasu Creek. The mean monthly values are from Sellers and others (1985) and the period of record is given in table 1.

much of the reported flood damage was caused by the failures of earthen dams in the headwaters.

The Flood of February 23, 1920

George J. Laben, superintendent of the Havasu School, to Commissioner Sells, described the next large flood in Havasu Canyon in a letter written on February 25, 1920:

> Warm rains continued intermittently from the 18th on, melting the snows of the surrounding country as far away as the mountains called the Frisco Peaks...The water in the creek [Havasu] which flows through this canyon began to raise gradually Sunday the 22nd, but this soon changed to a flood. The water raised from 6 O'Clock in the evening to 9 O'Clock the same evening 20 feet [6.5 m], leaving its bed over-spreading adjacent bottom lands along the creek. So rapid was the water in its mad flight down the canyon that the main creek moved its channel several times. At places the water had washed sand banks away 40 feet [12 m] in length and 10 to 12 feet [3-4 m] in depth. On account of this many second and third growth cotton wood trees were taken along with the stream. At places where the channel was not so deep the water spread over an area of 10 rods [5.0 m] across. About 5 to 6 acres [2.0-2.4 ha] of alfalfa in small patches was covered by sand to a depth of one-half to one-and-a-half feet [0.2-0.5 m]... As the water has made some deep and ragged washes in the soft sand...(National Archives Files, Washington D.C.).

Laben's description suggests that the 1920 flood was the largest since 1910, but the 1910 flood was worsened by failures of earthen dams. During this flood the creek rose more gradually than in 1910, giving residents of the canyon adequate time to seek high ground. The gradual rise may explain why this flood was less destructive to Supai than the 1910 flood. Following the extensive damage to riparian vegetation and cropland in 1910, the 1920 flood may have caused less damage because riparian vegetation had only barely recovered from the previous flood.

Precipitation at Williams and Grand Canyon was above normal during the first half of 1920 (fig. 5). In February, precipitation was three to-four times greater than normal; the latter half of the year was slightly drier than normal. The heaviest daily precipitation at Williams associated with the 1920 flood was 49 mm on February 20 and has a recurrence interval of 3 years. The total storm precipitation for February 19 - 22 was 120 mm, which has a 10-year recurrence interval and ranks ninth among 20th-century winter storms at Williams (appendix 4). The storm also caused significant floods in the Gila River Basin in central Arizona (Sellers and others, 1985).

The Floods of August 1921

On August 10, 1921, Laben wrote to the Office of Indian Affairs Commissioner (National Archives, Washington, D.C.) about the effects of flooding in Havasu Canyon on the creek and croplands. Laben's letter indicates that 20 mm of rain fell in 1 to 2 hours on August 8, resulting in a flash flood that caused the creek channel to change course several times. The flood eroded the creek's banks at "sharp bends in the river." Precipitation at Williams, Seligman, and Ashfork ranged from 63 to 71 mm for August 5-7.

In his letter of August 10, Laben expressed concern for the stability of several earthen dams upstream of the village in the Havasu Creek drainage basin and specifically referred to the "Griffin Cattle Dam," which was about 20 km southwest of Anita, Arizona (fig. 1b). Griffin Dam, about 6 m high and 2.4 km long, was about 80 km upstream of Supai. The superintendent noted several other cattle dams that potentially threatened the village, including Rock Tank, Cataract Canyon Tank, and W-Triangle or Red Hill Tank; it is not clear how many of these original dams still exist. Laben's concern about the flood hazard in Havasu Canyon was well founded. On August 27, 1921, he wrote:

> About 7:30 to 8:00 O'Clock or about two-and-a-half to three hours after the heavy electrical and rain storm had disappeared in its eastern direction, all of sudden there came down with a roaring rush water from the Cataract Canyon, swelling this creek to the height of 15 to 18 feet [4.6-5.5 m], and 200 or more feet [61 m] wide carrying it current, trees, brush, fence... (National Archives Files, Washington D.C.).

The flood caused extensive damage to croplands in the canyon bottom, although it is unclear whether or not it was worsened by the failure of cattle dams.

Rainfall at Williams and Grand Canyon was above normal in July and August, 1921, following

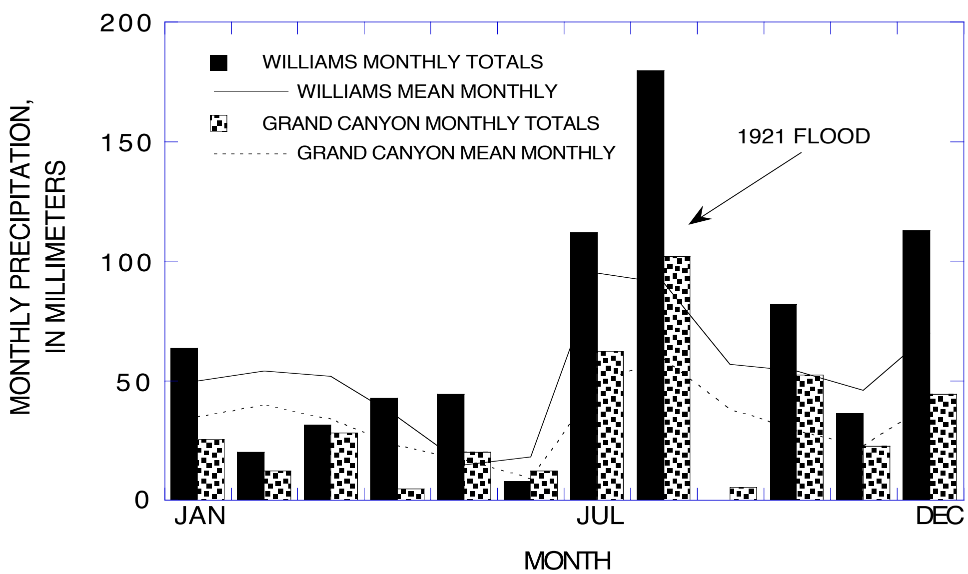
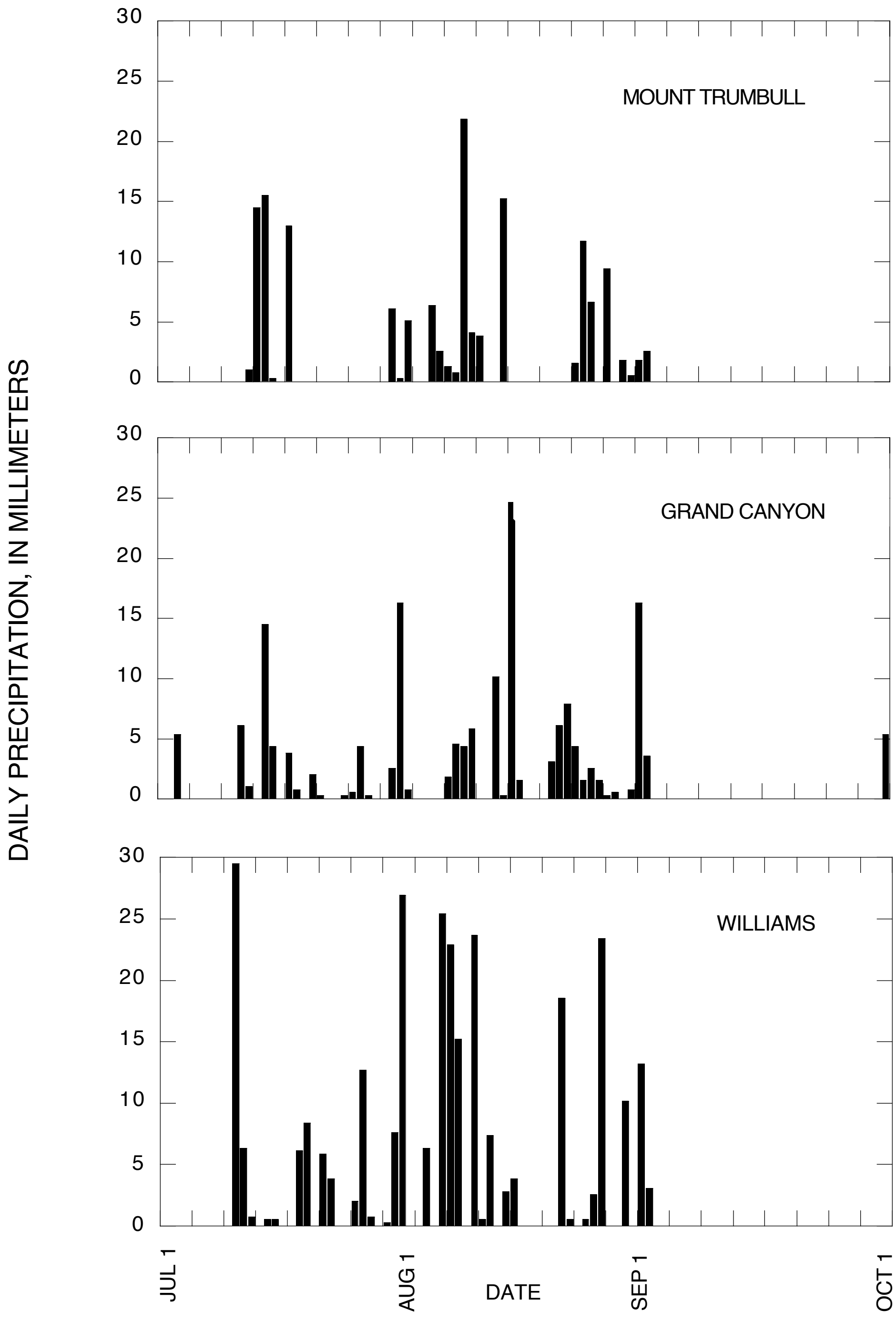


Figure 6. Rainfall associated with the August 1921 flood in Havasu Creek. A, Monthly rainfall at Williams and Grand Canyon, 1921. The mean monthly values are from Sellers and others (1985) and the period of record is given in table 1.



B, Daily rainfall at Williams, Grand Canyon, and Mount Trumbull from July 1 through September 30, 1921.

Figure 6. Continued

a relatively dry spring (fig. 6a). June through September rainfall was greater than normal during a monsoon season that lasted from early July to late August. Williams recorded more precipitation than the other stations, suggesting that the largest storms occurred in the southern part of the drainage basin. Daily rainfall in the vicinity of Havasu Canyon was highly variable during August 1921, which suggests that monsoonal storms were localized. Only Mount Trumbull recorded rainfall on either of the days flooding occurred at Supai. None of the August 1921 one-day rainfalls at Ashfork exceeded a 1-year recurrence interval; a storm total of 47 mm at Ashfork for August 5-7, 1921, had about a 2-year recurrence interval. The precipitation record suggests that flooding in the summer of 1921 was caused by local thunderstorms (fig. 6b).

The Flood of August 1, 1928

Patrick Hamley was superintendent of Supai in the late 1920s. During his tenure, Hamley witnessed a large flood that he documented in a letter dated August 2, 1928:

> Heavy flood struck Supai village about noon today [obviously referring to the previous day], without warning due to cloudburst or heavy rains. Chief Manakaja's wife drowned... Body recovered... About 15 families destitute... This flood was at its worst about 4:30 in the afternoon but lasted until about midnight on August 1st (National Archives Files, Washington D.C.).

Another account provided more details:

> Another cataclysm struck Havasu Canyon itself in the form of a disastrous flood. Havasu Canyon and indeed all the lower canyons draining into the Colorado are subject to flash flooding from storms above during the late summer. Usually these summer floods bring five to ten feet [1.5-3.0 m] of muddy run-off down the creek, which subsides after three hours or so. However, a heavy summer storm on August 1, 1928 brought a late afternoon flood that began at 4:30 P.M. and continued until midnight. Manakaja's 78-year old Havasupai wife Gwe gthgwaya was caught on a barbed-wire fence trying to flee the swirling waters and drowned. Winter floods are much rarer and less predictable (Hirst, 1976, p. 75).

No information on the geomorphic effects of this flood on Havasu Creek is available, and no historical photographs were found that encompass the date of the 1928 flood.

Rainfall at Williams and Grand Canyon was normal to below normal for July and August 1928 (fig. 7a), and the annual precipitation was normal. Daily precipitation records for three stations indicate high spatial and temporal variability of summer rainfall in 1928, and none of the largest daily precipitation totals corresponds to the date of the flood (fig. 7b). In addition, none of the daily rainfalls for August at any of the stations examined exceeded a 1-year recurrence interval.

The Flood of July 1935

An eyewitness account of a large flood that occurred in Havasu Canyon during the summer of 1935 was obtained from Mrs. Minnie Marshall at Supai in June 1991 (M. Marshall, Havasupai Tribe, oral commun.). Marshall resided in the village at the time of the flood and clearly recalled the 1935 flood. Marshall said the flood occurred in summer, but could not remember the exact date. All of the houses in Supai were inundated with water about "knee high;" one or two houses were washed away in the flood, but no one was seriously injured. Marshall also remembered that the 1935 flood washed away many trees. Having also witnessed the 1990 flood, Marshall thought both floods were approximately the same magnitude.

Rainfall at Williams and Grand Canyon was normal to slightly above normal in July 1935 (fig. 8). Most of the year had near normal rainfall except during January, which was wetter than normal at Williams. Precipitation records from Williams, Grand Canyon, and Mount Trumbull suggest local monsoonal storms occurred from mid-July through September. Rainfall was greatest around the southern part of the Havasu Creek drainage basin on July 17-19. The largest daily rainfall (56 mm) at Williams in July 1935, which occurred on July 18, has a 16-year recurrence interval and ranks 6th among the daily rainfall totals at Williams (appendix 4). Therefore, the most probable date for the flood is July 18, 1935.

Regional Flooding of 1939

Dissipating tropical cyclones can cause extremely large floods in the southwestern United States and are the prototype storm for probable maximum precipitation in the region (Hansen and others, 1977). September 1939, had extremely high rainfall in parts of California, Nevada, Arizona, and Utah, and typically is cited as one of the best examples of the effects of this type of storm (Hansen and Shwarz, 1981). From September 1 through 20, four tropical cyclones moved northwest along the west coast of Baja California, turned abruptly northeastward toward land, and dissipated over the southwestern United States (Smith, 1986). Tropical cyclones are rarely large enough to push inland as far as western Grand Canyon; the September 4-7 storm is an example of the meteorological conditions required for this type of storm to reach the southwestern Colorado Plateau (Hansen and Shwarz, 1981).

Rainfall at Williams and Grand Canyon (fig. 9) for September 1939 was three to five times higher than normal, whereas the rest of the year was relatively dry. Five stations near Havasu Canyon recorded from 179 to 219 mm of rainfall in September; three of five stations recorded the greatest rainfall on September 5, 1939. Although Gatewood and others (1946) reported flooding was widespread in northwestern Arizona and eastern California as a result of the dissipating tropical cyclones, no historical accounts exist for flooding in Havasu Creek during September 1939. Although the lack of flood accounts does not preclude flooding, any floods that occurred in Havasu Canyon in September 1939 were probably small.

Despite the lack of documentation of a 1939 flood, Joseph Muench, a professional photographer who photographed waterfalls in Havasu Canyon between 1936 and 1942, stated that Fiftyfoot Falls was eroded by floods sometime after 1937 (J. Muench, written commun., 1991). On the basis of

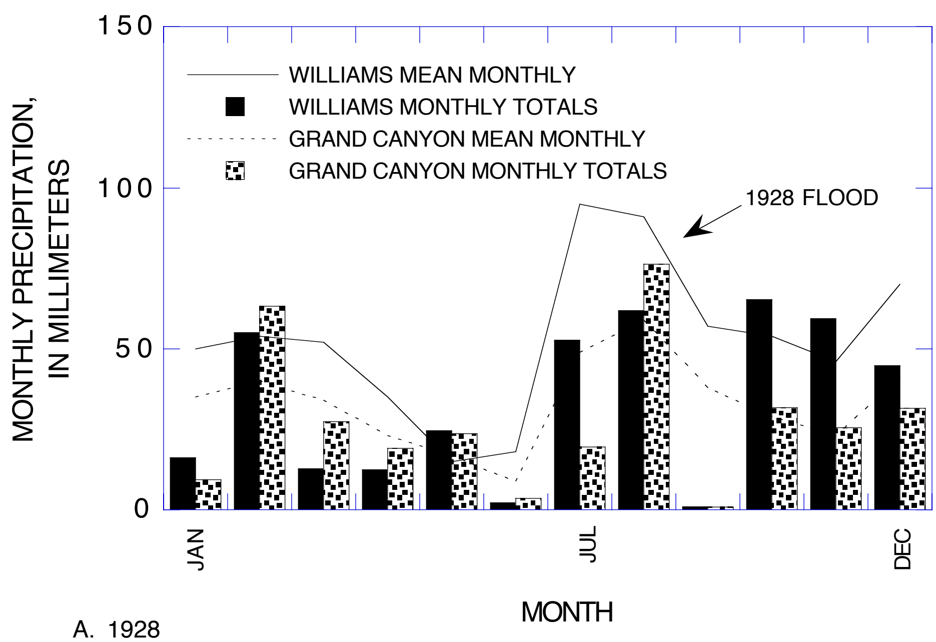
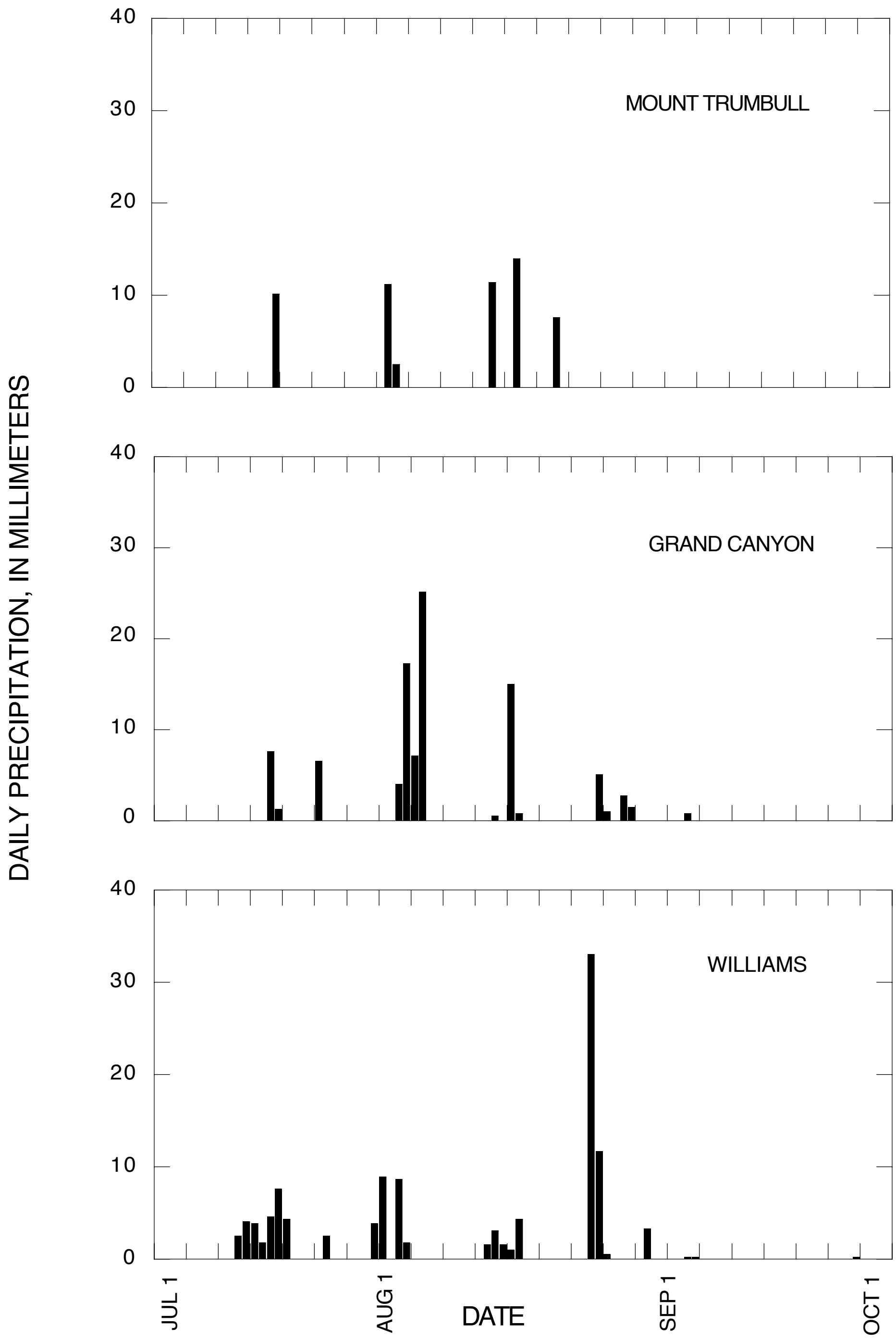


Figure 7. Rainfall associated with the August 1928 flood in Havasu Creek. A, Monthly rainfall at Williams and Grand Canyon, 1928. The mean monthly values are from Sellers and others (1985) and the period of record is given in table 1.



B, Daily rainfall at Williams, Grand Canyon, and Mount Trumbull from July 1 through September 30, 1928.

Figure 7. Continued.

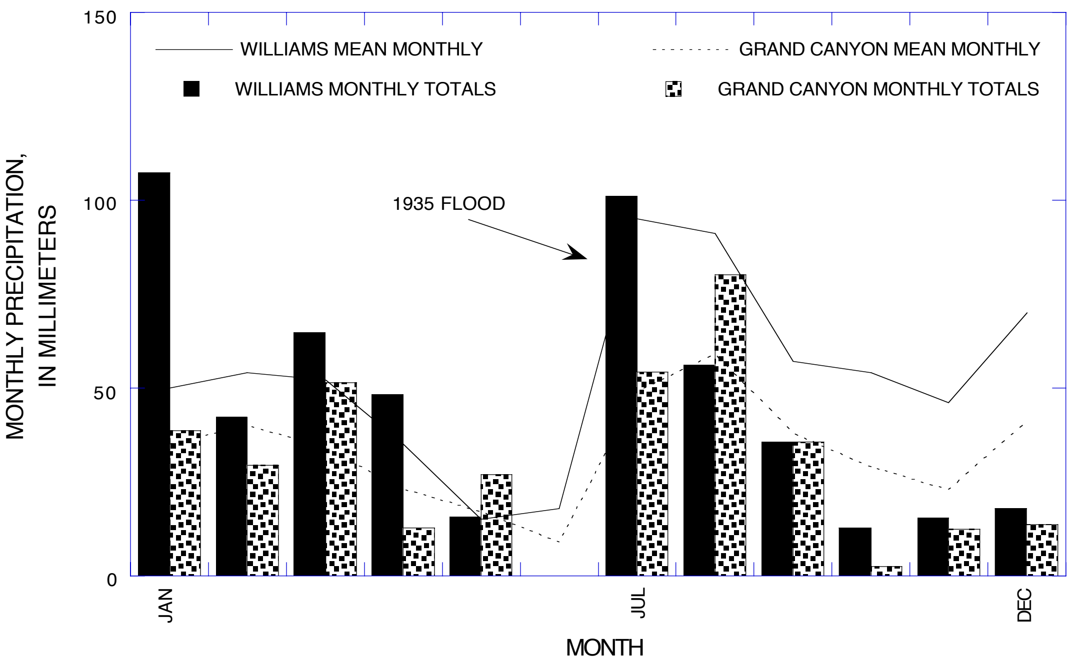


Figure 8. Rainfall at Williams and Grand Canyon associated with the July 1935 flood in Havasu Creek. The mean monthly values are from Sellers and others (1985) and the period of record is given in table 1.

this account, it is possible that Fiftyfoot Falls was eroded by flooding in September 1939.

Flooding from 1940 to 1970

Interviews were conducted in September 1994 with individuals who visited Havasu Canyon from 1940 through 1970 from Colorado River trips. Several of those interviewed had visited Havasu Canyon more than once, one as early as 1938, and were asked if they remembered damage to vegetation and (or) travertine deposits during their trips into the canyon. No one remembered seeing flood damage between Mooney Falls and the Colorado River from 1940 through 1970 (Lois Jotter Cutter, Bob Rigg, Lesley Jones, John Cross Jr., oral commun., 1994). Several individuals, however, expressed surprise at changes caused by flooding since 1990. Despite the 1990s floods, some boulders in Havasu Creek near the Colorado River were recognizable to one person, although he had not visited the canyon in about 30 years (Rigg, written commun., 1994).

Although river runners did not remember flood damage, small floods caused some changes in Havasu Canyon in the mid-1950s. Griffith (1963) noted flooding during August 1955 and discussed changes to the waterfalls and riparian vegetation caused by floods in 1954 and 1955:

> Before the flood of 1954, a strong hiker, pressing all the way, required twelve hours of actual hiking time for the round trip from village [Supai] to river [Colorado] and back. Now, however, time is reduced by about three hours, for the flood swept away a great amount of brush undergrowth... Fiftyfoot Falls... During the flood of August 1955, this fall was reduced from its former eminence to its present cascade-like status. Once it was of impressive height, spoke in strong tones, and had a fine trout-filled pool below. The flood not only reduced the fall, but swept away the trout, and efforts to re-establish them have not proven successful... Just a mile and a half below the village a whoosh and boom tells you that you have reached the first full-scale falls. These are Navajo Falls. In the past, the falls was broad and lacy with a drop of about seventy-five feet [23 m]. It is now divided into two distinct flows about sixty feet [18 m] high. The intervening rock gives some indication of being worn down once more. Perhaps in another five to ten years, this stream will again be broad and

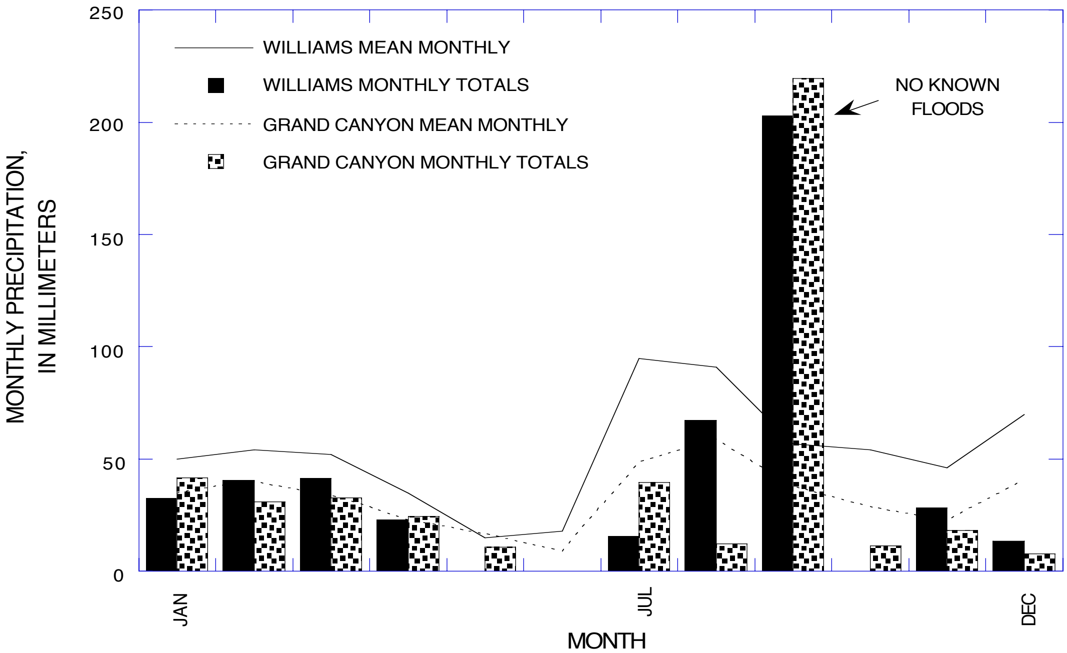


Figure 9. Rainfall at Williams and Grand Canyon in September 1939 that was not associated with a known flood in Havasu Creek. The mean monthly values are from Sellers and others (1985) and the period of record is given in table 1.

> lacy... In 1955, before the flood, Havasu [Falls] was a two-stream falls because of a stone divider in the center of the lip [presumably a travertine deposit]. The divider was torn away by the flood, and the stream plunges from a semi-circular shelf which has been carved out from the face of the cliff... For Havasu has been subject to change, although not as much as Navajo [Falls]. Perhaps its travertine overlay is of a more solid kind than that of Navajo and requires more water power than the usual winter or summer freshet to make a substantial change... (Griffith, 1963, p. 35-37).

Griffith's account indicates that both Fiftyfoot and Navajo Falls were eroded by the 1955 flood, and a flood in 1954 apparently damaged riparian vegetation between Supai and the Colorado River.

Attempts to stock rainbow trout in Havasu Creek were thwarted by the floods of the mid-1950s. O.L. Walls (National Park Service, written commun., April 7, 1964) reports that 18,600 rainbow trout fry were planted in April 1954. A flood in August 1954 destroyed the trout and altered the channel slightly.

Precipitation in Williams and Grand Canyon was above normal in March 1954, providing one possibility for a flood that year (fig. 10a). Another possible date for the 1954 flood is the first week of August, because rainfall ranged from 25 mm to about 40 mm in a day at Ashfork, Seligman, and Williams (fig. 10b). This may have been the flood that killed the trout fingerlings.

In the summer of 1955, rainfall at Williams and Grand Canyon was above normal (fig. 10a), but these precipitation records do not clearly indicate a date for the flood, which could have occurred either in July or August (fig. 10b). The Mount Trumbull data strongly suggests July 24 as a probable date for the flood, because the highest daily rainfall total of the record (111 mm) fell on that date (appendix 4). Although Griffith (1963) states that the flood occurred in August 1955, flooding could have occurred on June 13 or 24 (fig. 10c). The 1950s floods may have been the first significant ones in Havasu Canyon in 20 years.

Small Floods in the Summer of 1970

Several small floods were witnessed during the summer of 1970 by George Billingsley, at that time a NPS ranger stationed in Havasu Canyon. According to Billingsley, the floods he witnessed had no lasting effect on the morphology of the creek (G. Billingsley, U.S. Geological Survey, written commun., 1994). His accounts document typical thunderstorm-induced floods in Havasu Canyon.

On July 8, 1970, Billingsley described the first flood of the summer:

> I climbed up above the Redwall [Limestone cliffs] and watched a heavy rain in Supai. Only rained about 15/100 of an inch [3.8 mm] here. The north rim had heavy rains. Sure was cool and lightning was pretty thick. Later, about 45 minutes after the storm ended, a flood came down Havasu Creek about one foot [0.3 m] deep over Havasu Falls.

On July 21, Billingsley observed a larger flood as it reached Havasu and Mooney Falls:

> This afternoon I climbed up above the camp and watched a thunderstorm build up and give Supai a good rain... From where I sat I counted 7 waterfalls over the red cliffs [Redwall Limestone]... I went down to the creek and waited for the flood... 45 minutes later I got impatient and started up to Navajo Falls to watch. I crossed the foot bridge and then noted that water seemed to be lapping over it a little more than it usually does... Anyway, soon the water started to come up rather fast and I hot footed and danced back across just in time before the water covered the bridge... I ran down to Havasu Falls and yelled at everyone to get out of the water, because a flood was coming. They just looked at me and at the falls and went on swimming. Finally, one fellow recognized me as the ranger without my uniform on and hollered for his boys to get out. About that time Havasu Falls tripled its flow over the falls in a thundering roar and came so fast everyone was stunned and stared. Four or five of them had a heck of a time trying to reach the shore while being swept downstream in the suddenly strong current of muddy water. The falls became a huge muddy curtain and spray was blinding everyone who climbed out to look at it... I ran down to Mooney Falls after watching it about 3 minutes. To my surprise I had to run the whole mile and got there just as the flood started over. It really moves... The flood was only a foot deep [0.3 m] over Havasu Falls, which is about 20 feet [6 m] wide. This may not seem like a lot of water, but believe me it moves.

The following day (July 22), Billingsley witnessed a larger flood in the reach between Havasu and Mooney Falls. He included an

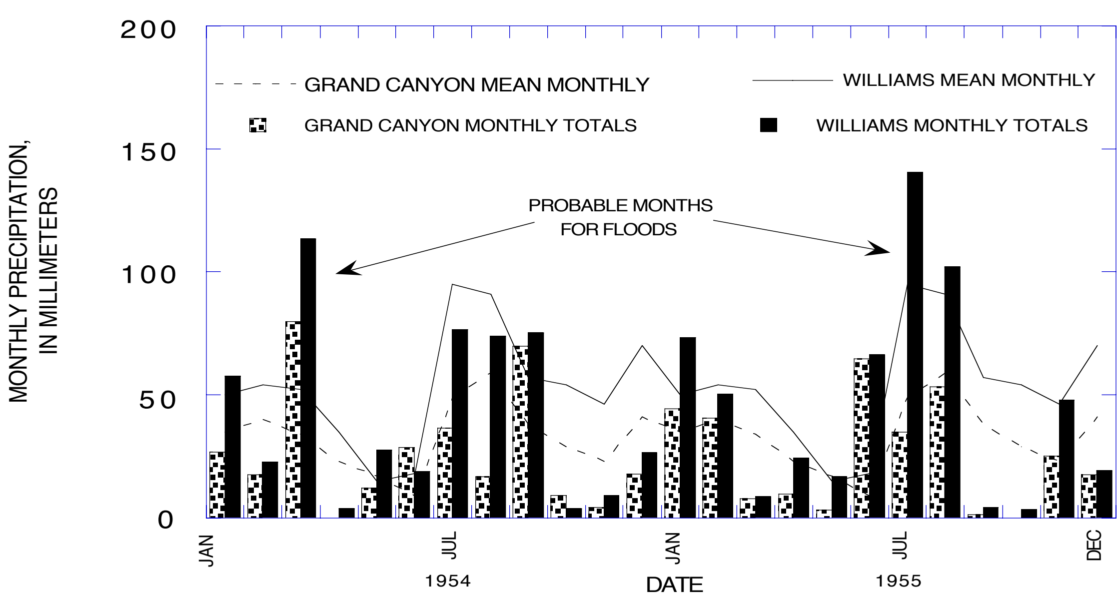
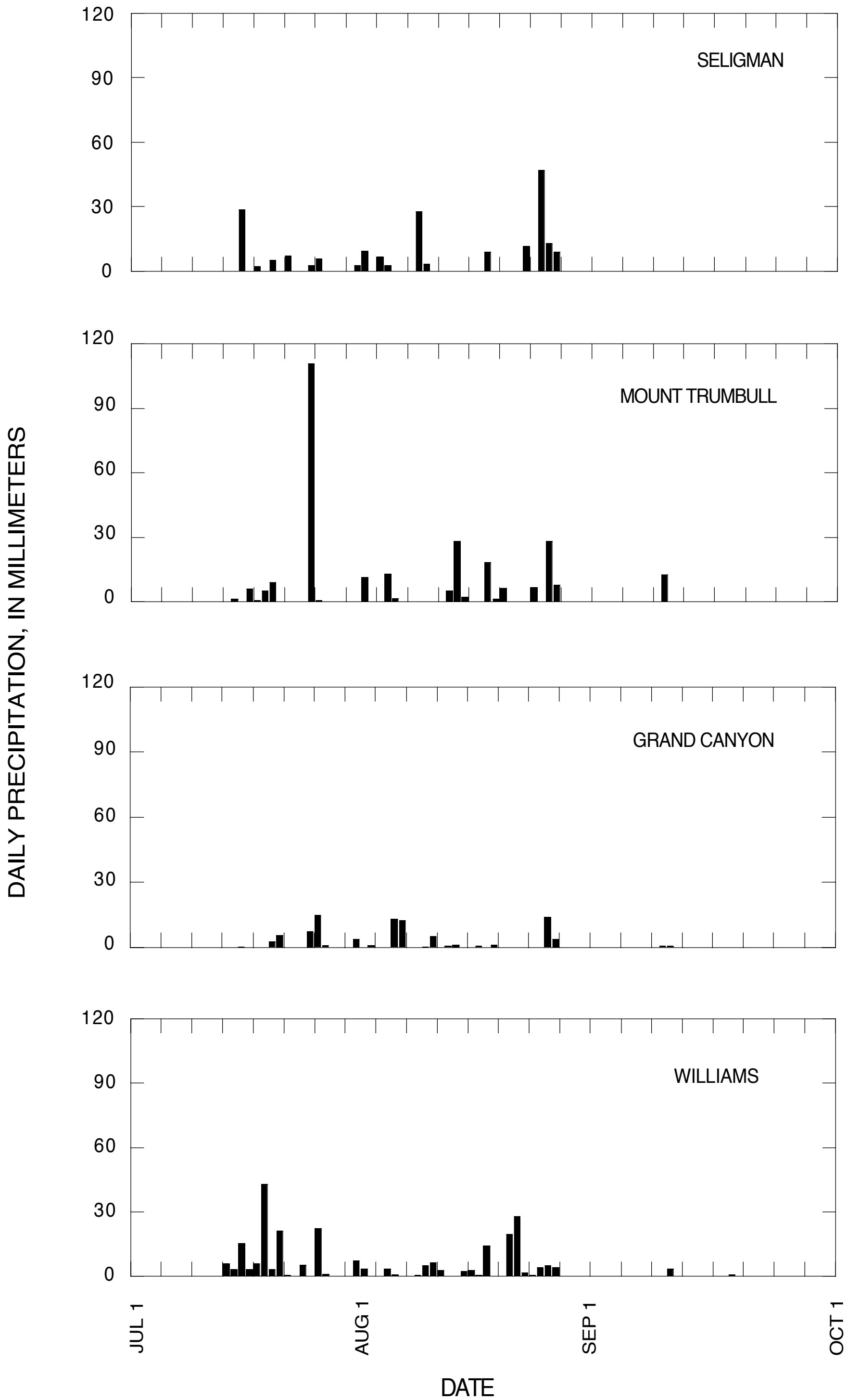


Figure 10. Rainfall associated with the 1954-1955 floods in Havasu Creek. A, Monthly rainfall at Williams and Grand Canyon, 1954-1955. The mean monthly values are from Sellers and others (1985) and the period of record is given in table 1.



B. Daily rainfall at 4 stations in the vicinity of Havasu Creek from July 1 through September 30, 1955.

Figure 10. Continued.

excellent description of the thunderstorm that caused the flood:

> I watched a bank of huge towering clouds to the north that made a wall of white as far east and west as I could see. There was a strong southwest almost west wind at cloud level... I sat and looked for hours. Mostly I watched the tremendous pile of clouds move ever steadily closer from the north. The clouds weren't moving from the north, but they were building up towards the south and only appeared to move from the north. This was a huge thunderstorm and even though it was 50 miles [80 km] or more away I could hear distant rumbling. In the afternoon a few clouds were towering around Supai, but not much. Also, the giant storm had gotten close enough to reach the north rim and clouds almost touched the rim. They towered up to a mighty height of at least 30,000 feet [9,144 m]. Tons of rain came over the north rim. The clouds around over head began to take on a heavy shape and build rapidly. I decided to stay for the onslaught of the storm. This beautiful monster was slowly eating up the canyon. When it was pouring into the Colorado River about 7 miles [11 km] away, the wind came up strong and cool. I found shelter in a small ravine overlooking all of Supai and to the north and east. The clouds overhead were very heavy and dark. Then it rained and rained. In no time at all water was dribbling all over the bare rock. This bench plateau is almost all solid rock like pavement and doesn't take much water to get started for the cliff. It poured over the cliff in huge waterfalls in all directions. For sometime I couldn't see anything. Lightning was close several times. It rained well over an inch. A cascade of water poured over the overhang... like someone dropped a curtain over me. It rained over the entire canyon clear up to the Hilltop [Hualapai Hilltop trailhead]. The sun came out as soon as it was over and rainbows, three strong, came out. I was amazed at the sight I saw then... I counted 72 waterfalls from my vantage point. I was speechless. Some of the muddy falls were pouring enormous quantities of water well up to a thousand feet [325 m] straight down to dissolve into a feathery spray of wavering curtains... I raced down the trail to the campground in record time... just in time to see the full flood come over Havasu Falls. Some people were trapped on the other side of the creek above the bridge and set up camp there... I came to find out later that many people were down at Beaver Falls and pretty well trapped with no food or clothing. The sight of the falls [Havasu] was unbelievable. Just over four feet [1.2 m] of water was churning over the 20 foot [6 m] gap [the notch] of the falls and spraying way out in a muddy rough curtain. The mist was very thick. I ran down into the lower part of the campground and dragged three picnic tables out of the knee-deep water. The flood was really cleaning the area. A fellow's tent and belongings were wiped away before he could get to them. Other people were moving up to the caves. I managed to wade the trail and get down to Mooney Falls... what a sight. It was the biggest falls I've ever seen as far as quantity of water over the 200 foot [61 m] drop. The mist was too thick below to see the water plunging into the muddy mist. The large 60 foot [18.3 m] cottonwood trees were gone obscured under boils of brown mist.

Billingsley reported that another large flood occurred on the evening of July 23. Although he did not witness this flood, he estimated its depth at slightly more than 1 m through the Havasupai campground from high-water marks. On July 29, after returning to his duty station in the canyon and learning of the most recent flood, Billingsley noted:

> That makes four floods so far this summer over Havasu Falls and 3 floods down Carbonate Canyon. The water level below the swing at Havasu Falls had dropped 18 inches [0.46 m] and now you could hit bottom easily when jumping off the swing. Things have changed along the creek from all the floods. Lots of boulders have come out of Carbonate Canyon. Some dams have been smashed, but not bad.

Two small floods occurred between August 1 and 16 that had virtually no impact on the channel. Then, on August 17, he witnessed one of the summer's most violent floods as it arrived at the Colorado River:

> Suddenly a large mass of muddy bright red water shot out of the narrow walls of Havasu Creek and formed a small tidal wave that nearly went all the way across the Colorado River. Its speed and suddenness scared me. The flow was moving close to 20 miles per hour [32 km/hr]. I was amazed at the power of that flood. I wondered if those two [his hiking

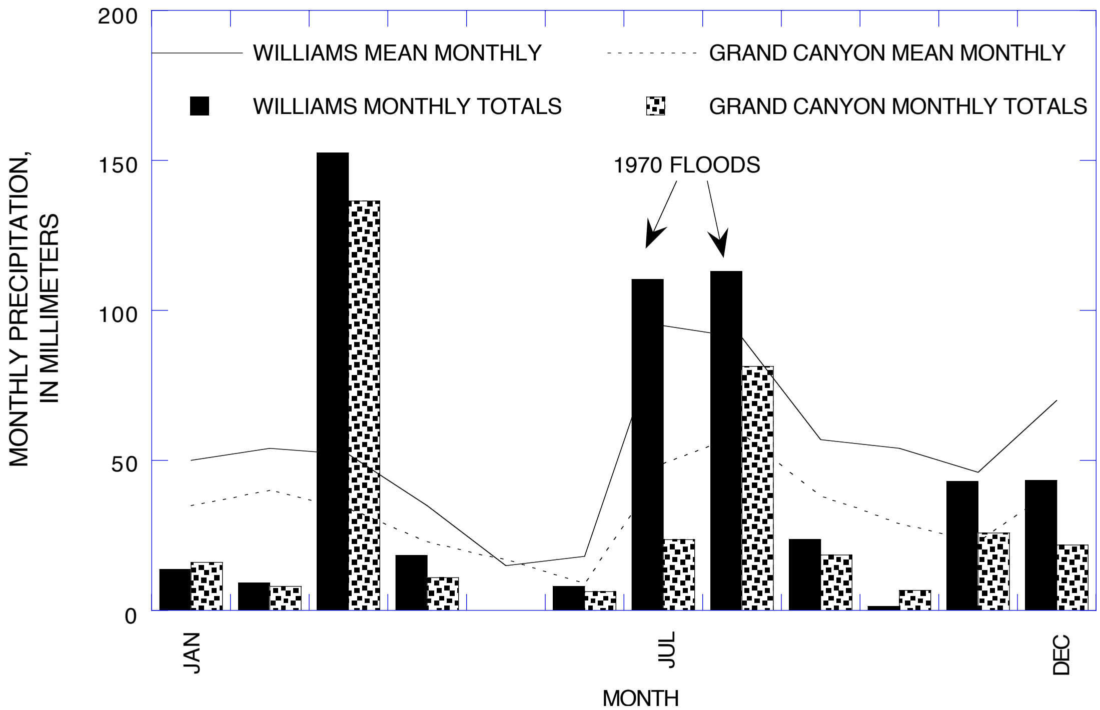


Figure 11. Rainfall at Williams and Grand Canyon associated with the 1970 floods in Havasu Creek. The mean monthly values are from Sellers and others (1985) and the period of record is given in table 1.

> partners from earlier in the day] had managed to get out of the way. I felt sure this flood came from Beaver Canyon. I ran up to the first crossing and took pictures. It was a very impressive sight. The flood averaged 4 feet [1.2 m] deep and 15 yards [13.7 m] across. So I settled down and waited for the flood to go down. It took two hours for it to get low enough for me to attempt crossing.

Billingsley witnessed two more flash floods on August 18 that he described as being about a half-meter deep at the top of Havasu Falls. On August 20, 1970, Billingsley recorded another small flash flood at Havasu Falls making a total of 10 that summer.

Rainfall at Williams and Grand Canyon was above normal in the vicinity of the Havasu Creek drainage basin during March, July, and August 1970 (fig. 11). Nine stations within 120 km of Supai (table 1) recorded highly variable rainfall on the dates that Billingsley reported floods. For example, rainfall at Seligman on July 21, 1970, totaled 123 mm — nearly five times that of Supai (25 mm) — and contrasted sharply with Billingsley's description of light rain near Supai before the second largest flood. Despite this difference, daily precipitation records for July 1970 agree well with dates of floods. Rainfall for the storm recorded at Supai for July 21-23 (53 mm) has a recurrence interval of 20 years and is ranked 2nd in the record.

The floods experienced by Billingsley in the summer of 1970 were generated by local thunderstorms, several at a considerable distance from Havasu Canyon. Billingsley's July 21 and 22 accounts underscore the fact that little warning typically occurs before floods caused by distant thunderstorms. Individuals who visited Havasu Canyon from 1938 to 1990 reported that small floods like the ones described by Billingsley are typical of those that occurred during the middle part of the 20th century. This type of thunderstorm-induced flood poses a significant risk to visitors in the lower canyon, although such floods are rarely large enough to significantly alter waterfalls and pools or threaten buildings in Supai.

The Floods between 1970 and 1990

Professional river guides who ran the Colorado River regularly between 1970 and 1990 observed many small floods in Havasu Creek. Some of the guides interviewed had visited the lower part of

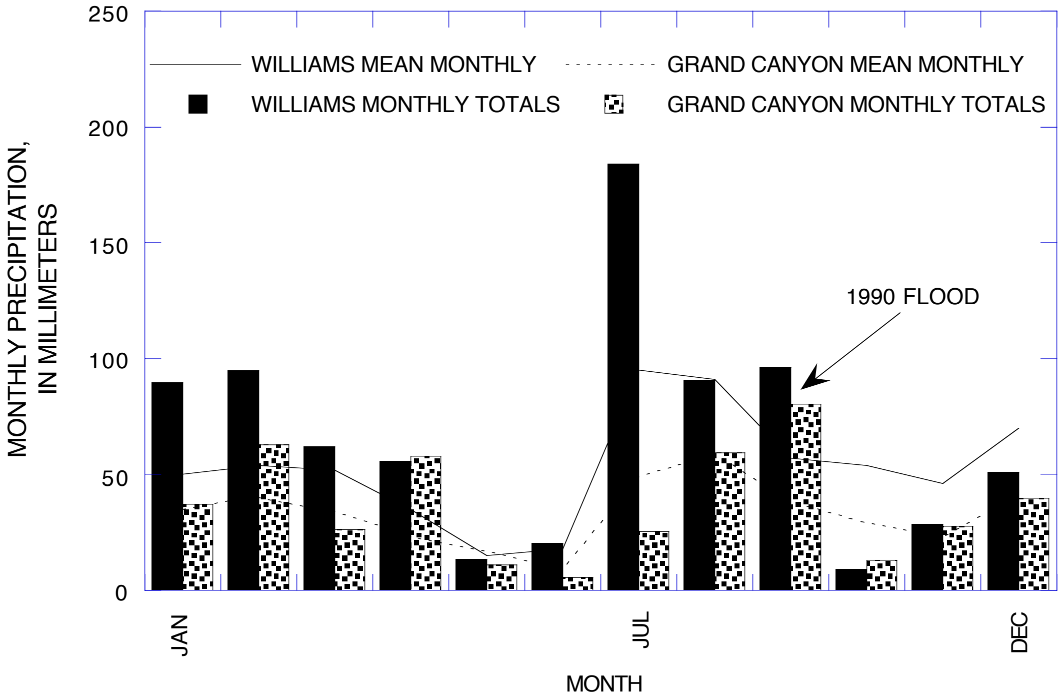


Figure 12. Rainfall at Williams and Grand Canyon associated with the September 1990 flood in Havasu Creek. The mean monthly values are from Sellers and others (1985) and the period of record is given in table 1.

Havasu Canyon 100 to 200 times during the 20-year period. The guides gave several accounts of summer floods comparable to those described by Billingsley in 1970, but none could remember flooding close to the magnitude of a flood that occurred in 1990 (Dennis Silva, Gary Bolton, Kenton Grua, Tim Whitney and Larry Stevens, oral commun., 1994). Between 1970 and 1990, riparian vegetation became very thick in Havasu Canyon, and a trail system was developed for hikers to easily move through the canyon.

The Flood of September 3, 1990

On the basis of historical accounts, the flood of September 3, 1990, was the largest in Havasu Canyon since 1935, and possibly since 1910. Widespread monsoonal thunderstorms occurred over northwestern Arizona from September 1-5; moisture advected from the Pacific Ocean off the Mexican coast caused heavy rainfall throughout northwestern Arizona, particularly on September 2. Surface-pressure maps for the western United States for August 31 through September 5 (not shown) document persistent low pressure over southeastern California, which, combined with the moist air flow from the Pacific Ocean, created thunderstorms in northwestern Arizona.

Rainfall during September 1990 was above normal at both Williams and Grand Canyon following a strong summer monsoon that began in July (fig. 12). The highest daily rainfalls occurred in July and late September; most precipitation stations in the vicinity of Havasu Canyon recorded rainfall less than 25 mm for September 1-5. None of the days with the highest rainfall coincided with the September 3 flood date. Antecedent moisture in the Havasu Creek drainage basin may have significantly affected the magnitude of the 1990 flood. Although none of the daily rainfall totals exceeded a 5-year recurrence interval, an August storm of 151 mm at Ashfork from August 12-16 ranked first among storms and had a recurrence interval of 139 years (appendix 4).

The 1990 flood caused severe damage to Supai when "a 14-foot [4.3 m] wall of water" hit the village (*Flagstaff Daily Sun*, September 6, 1990). It is not useful to compare the "14-foot wall of water" in 1990 with the "wall of water 20 feet high" reported in 1910 because Supai was moved downstream after the 1910 flood to a wider reach of the canyon (fig. 1c). The 1990 flood stranded 60 tourists, who eventually were helicoptered out of Supai, and several horses were the only fatalities. Several hundred to a thousand ash and cottonwood trees of various sizes were uprooted and flushed from Havasu Canyon by the flood. Most of the travertine pools downstream of Mooney Falls were partially or completely destroyed; flow became channelized through partially-eroded pools. Damage to travertine deposits between Supai and Mooney Falls also occurred, but the erosion was not as severe as in the pools downstream.

Newspaper accounts provide some additional perspective on the magnitude of the 1990 flood:

> Severe flooding in the Havasupai Canyon, about 80 miles [129 km] north of Flagstaff, prompted Coconino County to declare a state of emergency there Tuesday... Twelve houses have been damaged by the flood, including two which were lifted from their foundations... Heavy rains sent rushing water from the Williams area, near the headwaters of a creek in adjacent Cataract Canyon, to Havasu Creek and through the village until Tuesday evening, tearing Cottonwood trees at their roots and stranding animals in three feet [1 m] of mud... The flood also wrecked the tribe's water and sewer systems; cut electricity and phone service; reportedly killed many pets and livestock; and drowned about 500 acres [202 ha] of cropland (*Flagstaff Daily Sun*, September 6, 1990).

Like previous floods, the 1990 flood was large enough to disrupt agriculture on the bottomlands and to damage houses in Supai.

The peak discharge for the 1990 flood was estimated indirectly using the slope-area method (Dalrymple and Benson, 1967). High-water marks were surveyed about 1.6 km upstream of the gaging station (fig. 1c) in October 1990. The channel at the gaging station changed dramatically during the flood; most of the trees and other bottomland vegetation were uprooted from the channel banks, and the remaining trees were bent over or broken and stripped of leaves and bark. Sand deposits on the left bank were removed and replaced by cobbles and boulders, some of which were lodged in ash trees 2 m above the eroded stream bed. High-water marks were found mostly on near-vertical bedrock walls; at the gaging station, high-water marks had a gage height of 8.0 m. Typical baseflow at this station has a gage height of about 2.5 m and the gage height of zero flow is 1.9 m.

The computed peak discharge of the 1990 flood was 575 m^3/s (R.H. Roeske, U.S. Geological Survey, written commun.), and the computation was rated as fair; unit discharge was 0.079 cubic meters per second per square kilometer ($m^3/s/km^2$). The average velocity for the 1990 flood was 6.0 m/s, a value that is relatively high, but consistent with other 1990s floods in Havasu Canyon, and with Billingsley's accounts of 1970 floods. The 1990 flood had an estimated recurrence interval of about 25 years using regional-regression relations (Thomas and others, 1994).

A videotape showing the channel of Havasu Creek between the confluence with the Colorado River and Supai was made from a helicopter about 2 weeks after the flood (GCES files, Flagstaff, Arizona) and documents major changes to the creek channel downstream from Mooney Falls. Damage to bottomland vegetation along the creek in the reach closest to the Colorado River was not as severe as in the reaches upstream. Although tributaries to Havasu Creek below Supai contributed a significant but unknown amount of flow, the main flood wave originated in Cataract Canyon upstream of Supai. The 1990 flood increased the channel erosion upstream of Havasu Falls that had occurred in 1910. Large cobbles and boulders were deposited in the Colorado River, although the deposition did not form a distinct debris fan at the mouth of Havasu Creek.

The Flood of July 25, 1992

Two notable floods followed the 1990 event. The first, on July 25, 1992, resulted from summer thunderstorms directly over Havasu Canyon. The amount of precipitation is unknown because the rainfall station at Supai was discontinued in 1987 (table 1). Precipitation at Williams and Grand Canyon in March, May, August, and December, 1992, was above normal (fig. 13); July rainfall was almost twice the long-term average at Williams, but about average at Grand Canyon. Monsoonal storms were most intense from late July through August, on the basis of daily rainfall data. Using only the precipitation record, there is little evidence to suggest that a flood occurred on July 25. In 1992,

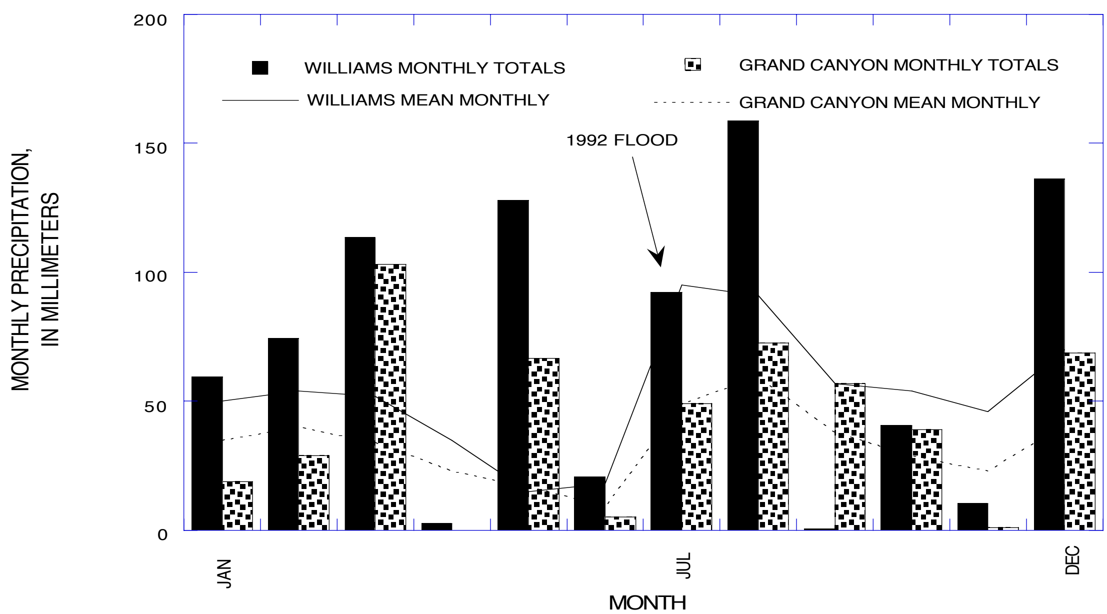


Figure 13. Rainfall at Williams and Grand Canyon associated with the July 1992 flood in Havasu Creek. The mean monthly values are from Sellers and others (1985) and the period of record is given in table 1.

the greatest daily rainfall recorded near Havasu Canyon occurred at Williams on July 31 (51 mm) and was part of a storm (101 mm; July 31 - August 6) with a recurrence interval of about 10 years. Thus, the storm that caused the 1992 flood probably covered a small area centered over the drainage basin.

On July 25, 1992, the peak discharge and gage height recorded at gaging station were 95 m^3/s and 4.8 m, respectively. High-water marks rated good to excellent were surveyed near the gaging station on August 4, 1992. An indirect-discharge estimate, based on the high-water marks that reached a stage of 5.1 m, yielded a peak discharge of 119 m^3/s, which was judged to be more accurate than the gaged discharge; the unit discharge is 0.023 $m^3/s/km^2$ and the average velocity is 3.4 m/s. The channel bed in the reach near the gaging station had aggraded with 2.7 m of sand, coarse gravel, and cobbles, and most riparian vegetation that had become established after the 1990 flood was removed from the channel banks. The maximum gage height of zero flow after the 1992 flood is unknown, but on the basis of photographs taken before the flood, its height must have been raised by about 0.6 m. The hydrograph of the 1992 flood (fig. 14) has the abrupt rise and fall that is typical of flash floods in Arizona. The flood was estimated to be a 2-year event on the basis of regional flood-frequency relations (Thomas and others, 1994).

Sediment was deposited at the mouth of Havasu Creek during the 1992 flood, enlarging the debris fan at the confluence with the Colorado River. Before July 1992, the confluence was a large area of quiet, deep water where 6-m long river rafts were easily moored. Afterwards, the mouth of Havasu Creek was filled with coarse sand, gravel, cobbles, and small boulders, severely limiting the size and number of boats that could moor there. Havasu Creek Rapid changed during the July 1992 flood because boulders and cobbles were deposited along the left bank of the river.

The 1992 flood eroded travertine deposits and vegetation along Havasu Creek and deposited sediment throughout the lower reaches of the canyon. Particle-size and source lithology data, obtained by point counting (see Melis and others, 1994) clasts on a debris bar, show that the flood transported mainly gravel derived from Redwall and Muav Limestone (fig. 15). The prior location of the gravel is unclear, and the 1990 flood reportedly did not redistribute gravel in the canyon. The gravel may have been eroded from travertine pools or talus slopes that were partially eroded

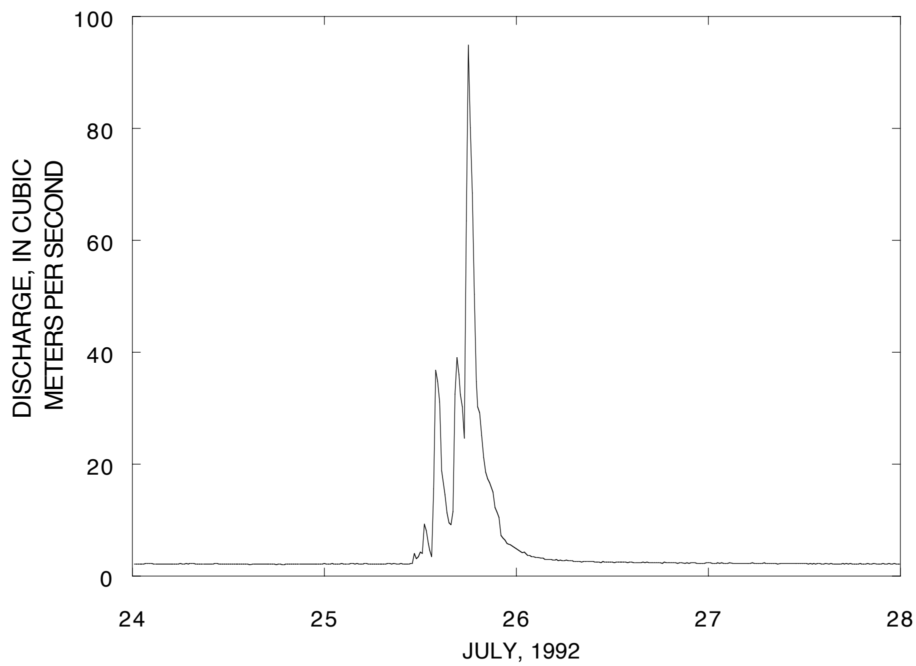


Figure 14. Streamflow in Havasu Creek at the Colorado River from July 24 through 28, 1992.

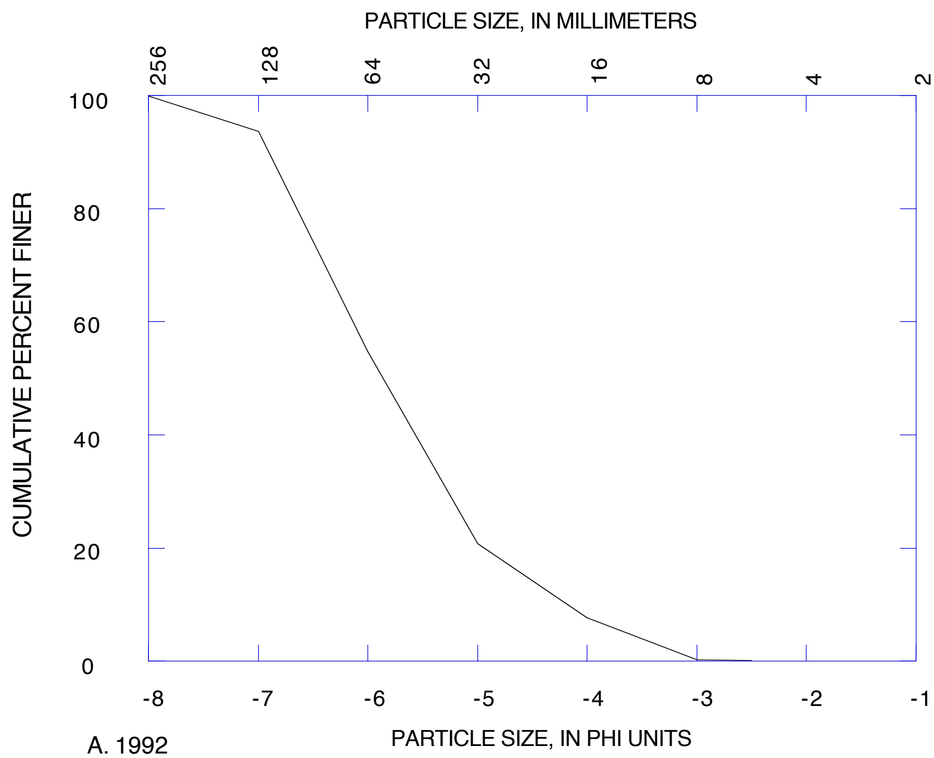
during the 1990 flood. The 1992 flood apparently had sufficient energy to entrain and transport the gravel and redistribute it throughout the lower canyon.

The Flood of February 20, 1993

An unusual series of warm, moist eastern Pacific Ocean storms, beginning early in January and continuing into late February 1993, caused heavy and occasionally prolonged precipitation across Arizona. The storms followed an extremely wet December, during which precipitation was 400% of normal in southwestern Arizona (Guttman and others, 1993). In January, the heaviest rains occurred in the central and southern parts of the state. In February, the heaviest precipitation occurred in the northern third of Arizona; near Flagstaff and Williams, much of the precipitation fell as rain, which melted a snow pack that began accumulating in November 1992. Precipitation in January and February was four-to-five times higher than normal at Williams and two-to-three times higher than normal at Grand Canyon (fig. 16); in contrast, precipitation for the remainder of 1993 was normal or only slightly above normal.

The largest daily precipitation in the winter of 1993 — 90 mm — occurred on February 20 at Williams and is the largest of the record with a recurrence interval of 157 years (appendix 4). The three-day storm of February 19-21 dropped 147 mm of precipitation, which is the 2nd largest winter storm on record and has a recurrence interval of 57 years. The high daily precipitation following an extremely wet period provides one of the clearest explanations for a Havasu Creek flood since 1910.

Flood damage occurred throughout northern Arizona in both January and February, 1993. The January storms were large, but little runoff occurred in Havasu Creek. On February 20, Supai and the Havasupai campground sustained extensive flood damage. The Bureau of Indian Affairs (BIA) described the flood as larger than the 1990 flood. Heavy runoff basin-wide overtopped and caused the collapse of several livestock tanks and small earthen dams, including Redlands Reservoir on Cataract Creek (fig 1b). The capacity of the Redlands Reservoir (fig. 1b) at the time of its failure was estimated at 90,700 m^3 (E. Westmann, Stetson Engineering, oral commun., 1994), and the breach resulted in a flood wave about 4 m deep that flowed down Cataract Creek toward Supai. Markham Dam, on Monument Creek (fig. 1b), also failed



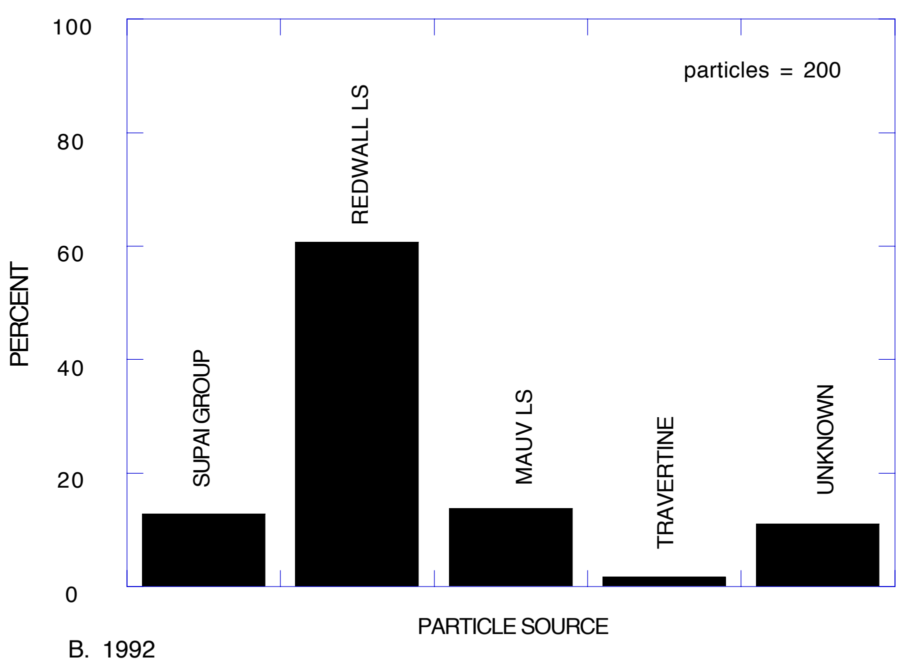


Figure 15. Particle data for coarse debris deposited in Havasu Canyon near the Colorado River. A, Particle-size distribution of coarse debris deposited in lower Havasu Canyon about 200 m upstream from the Colorado River during the flood of July 25, 1992. B, Source of coarse particles deposited in lower Havasu Canyon about 200 m upstream of the Colorado River during the flood of July 25, 1992.

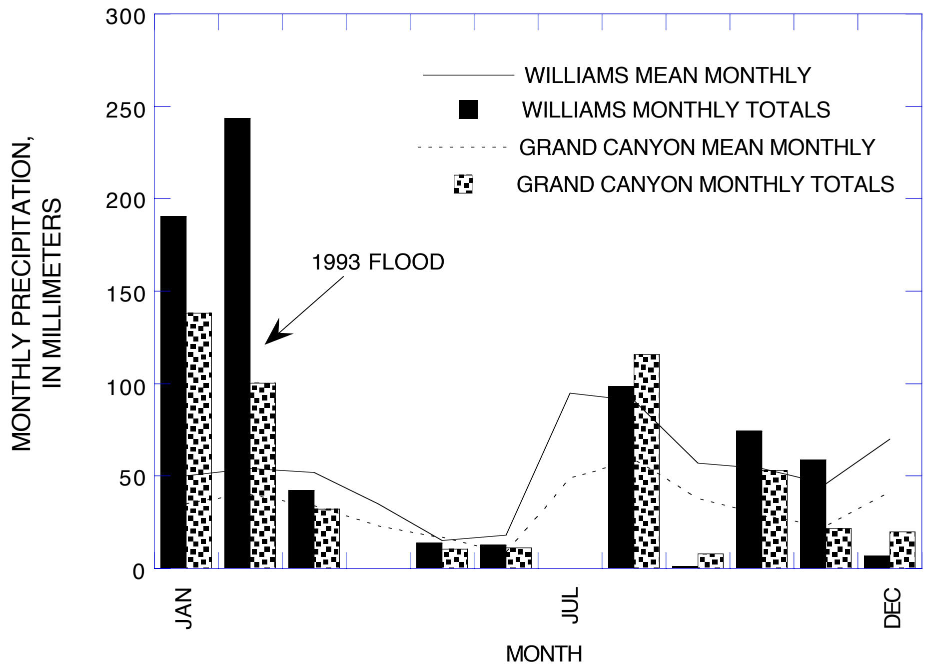


Figure 16. Precipitation at Williams and Grand Canyon associated with the February 1993 flood in Havasu Creek. The mean monthly values are from Sellers and others (1985) and the period of record is given in table 1.

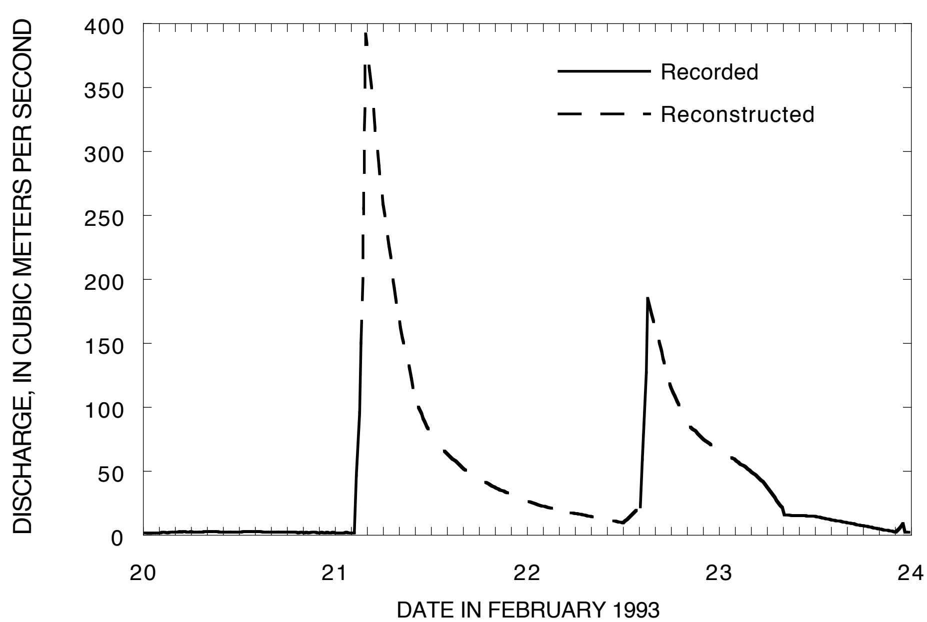


Figure 17. Streamflow in Havasu Creek above its mouth near Supai from February 19 through 23, 1993. Dashed lines indicate periods of reconstructed gage heights.

during the February storm; at the time of the February flood, its reservoir contained 90,000 to 100,000 m^3 of water (E. Westmann, Stetson Engineering, oral commun., 1994).

From surveyed high-water marks, the peak discharge and gage height for the February flood on Havasu Creek were 391 m^3/s and 7.1 m, respectively, at the gaging station. The velocity was 4.1 m/s. Zero gage height was 1.7 m, or 0.2 m lower than any previous measurements, but photographs taken of the reach before the flood revealed that the channel had aggraded during the February flood. This indicated a channel scour in the gage reach of about 1 m since the July 1992 flood. The recorded gage height for the peak of the 1993 flood was considered inaccurate because the gaging station was damaged during the flood. The recorded peak stage may have been superelevated by as much as 1.7 m owing to blockage of the station's orifice line; if this higher stage were valid, the peak discharge and gage height were 750 m^3/s and 8.8 m, respectively, and the 1993 flood would be larger than the 1990 flood.

To reconcile the discharge estimates, a slope-area estimate was made in the reach upstream from the gaging station. The peak discharge was 281 m^3/s, and despite the fact that the estimate was judged to be poor, the indirect-discharge estimate is a better approximation of the peak discharge of the 1993 flood. The unit discharge is 0.039 $m^3/s/km^2$. The recurrence interval for the 1993 flood was estimated at 5 years from regional flood-frequency relations (Thomas and others, 1994).

The reconstructed gage record indicates that the peak discharge occurred at 3:45 A.M. on February 21, 1993 (fig. 17). A second peak of about 188 m^3/s with a gage height of 5.8 m occurred at 3:00 P.M. on February 22. Comparing the February 1993 hydrograph (fig. 17) with that of the July 1992 flood (fig. 14) shows the differences between winter and summer flooding in Havasu Creek; the 1992 flood had a larger peak discharge, but was of shorter duration than the 1993 flood.

The 1993 flood aggraded the debris fan at the Colorado River. The deposit consisted of rounded cobbles and small boulders that likely were scoured from the channel of Havasu Creek. The riparian vegetation that survived the 1992 flood or became established afterwards was damaged again in the reach downstream from Mooney Falls; only a few young trees and grasses remained adjacent to the channel following the February 1993 flood.

Summary of Historical Flood Accounts

Written and oral accounts of floods in Havasu Canyon from 1899 through 1993 suggest a pattern of flooding during the late-19th and 20th centuries. General characteristics for historical Havasu Creek floods, their impacts to resources of the lower riparian corridor, and the types of storms associated with them are summarized in table 3. On the basis of historical accounts over the last century, early floods that damaged Supai, eroded the channel, altered waterfalls, and destroyed or degraded bottomland vegetation, crops and croplands frequently from 1899 through about 1935. All known floods occurred during either winter or summer. From about 1940 to 1990, large floods in Havasu Canyon were not reported, but several small floods during the mid-1950s and in 1970 were recorded in written accounts. Other visitors to Havasu Canyon during that period reported only small floods. The decrease in flood magnitude from 1940 to 1990 allowed for the establishment of dense riparian vegetation, and development of numerous large travertine pools, while headward channel erosion upstream of Havasu Falls, which began in 1910, ceased by mid-century. All floods from 1920 through 1992 resulted from localized summer thunderstorms. Very little is known about floods in Havasu Canyon before 1910. The January 2, 1910 flood was certainly the largest and most destructive flood documented in the historical record, and completely destroyed Supai. Floods from 1920 through 1935 occurred frequently and were damaging to riparian resources of the creek. Floods between 1940 and 1990 caused relatively less damage to resources of the stream channel, the bottomland ecosystem, or the travertine pools and waterfalls.

Three large floods occurred in 1990, 1992, and 1993. The floods of the 1990s damaged Supai and channel reaches upstream and downstream in a manner similar to the floods between 1899 and 1935, but was not close to the magnitude of the 1910 flood. The severity of at least two historical floods — in 1910 and 1993 — was increased to an unknown extent by failure of earthen dams in the

Table 3. Summary characteristics of historic floods in Havasu Creek

[n.d., no data or uncertain date; a, minor vegetation damage; b, vegetation scoured and pools eroded; c, Supai damaged; d, crops/croplands destroyed/degraded; e, waterfalls eroded; f, flood-related human fatality; 1, gaged or indirect; 2, approximate date from historical accounts; 3, exact date inferred from precipitation, 4, poorly known - no evidence for exact date; I, earthen dam failure(s); II, flood peak from rainfall on existing snowpack; W, Williams; SU, Supai; A, Ashfork; GC, Grand Canyon; MT, Mount Trumbull; +, above normal; =, about normal; -, below normal]

Year of Floods	Type of storm	Effects on Riparian Resources	Certainty of Flood Data	Extenuating Circumstances of Flooding	Monthly Precipitation, Verses Mean	Highest Daily(D) Precipitation (millimeters)	Total Storms Precipitation (millimeters)	Recurrence Intervals, D/S (years)
1899	Thunderstorm	b,d,e,f	4	---	n.d.	n.d.	n.d.	-/-
1904	Thunderstorm	c,d	3,4	---	W+	19(W)	42(W)	<1/<1(W)
1905	Frontal	c,d	3,4	---	W+	51(W)	99(W)	2/5(W)
1910	Frontal	b,c,d,e,f	2	I,II	W+	56(W)	75(W)	5/3(W)
1920	Thunderstorm	b,c,d	2	---	W+,GC+	49(W)	120(W)	3/10(W)
1921	Thunderstorm	b,c,d	2,3	---	W+,GC+	n.d.	47(A)	-/2(A)
1928	Thunderstorm	b,d,f	2	---	W-,GC+	17(GC)	53(GC)	1/1(GC)
1935	Thunderstorm	b,c,d,e	2,3	---	W+,GC+	56(W)	68(W)	16/1(W)
1954	Thunderstorm	b	2,3	---	W+,GC+	38(W)	90(W)	1/2(W)
1955	Thunderstorm	b	2,3	---	W+,GC=	111(MT)	112(MT)	-/-
1970	Thunderstorm	a	2	---	W+,GC+	25(SU)	53(SU)	2/20(SU)
1990	Thunderstorm	b,c,d	1	---	W+,GC+	20(A)	61(A)	1/1(A)
1992	Thunderstorm	b	1	---	W+,GC=	17(GC)	18(GC)	1/1(GC)
1993	Frontal	b,c,d	1	I	W+,GC+	90(W)	147(W)	157/57(W)

headwaters of the drainage basin (table 3). Low recurrence intervals for daily and storm totals associated with the 1910 flood, suggest that extenuating circumstances, such as dam failures and rainfall on snow, greatly increased the flood's destructiveness. In contrast, the high recurrence intervals for daily and storm totals associated with the 1993 flood make it difficult to evaluate relative to extenuating circumstances, such as effects of earthen dam failure in the headwaters.

Newspaper flood accounts and stream-gage data from 1990 through 1993 suggest that the floods in the 1990s were comparable to those between 1899 and 1935 although the 1910 flood appears to have been larger and caused more damage. The 1990s floods may represent a return to the more dynamic flood conditions of the late 19th and early 20th centuries in Havasu Canyon.

The amount of precipitation recorded at climatic stations may not be indicative of the magnitude of floods in Havasu Canyon. Most large floods occurred in wetter than normal months, regardless of season, but floods do not always occur in the wettest months, years, or even on the wettest days (table 3). In some cases, floods were not reported in wet months or following the largest daily rainfalls. Floods during the first third of the 20th century were caused by either winter frontal storms of regional scope or local summer thunderstorms. No known floods in Havasu Canyon were caused by dissipating tropical cyclones.

The precipitation record from Williams had the best relation to known floods in the Havasu Creek drainage basin, possibly because Williams is representative of the higher-elevation headwaters of the drainage basin. Daily precipitation ranging from 25 to 75 mm typically occurred at stations near Havasu Canyon on dates of large floods (table 3). Precipitation was usually from 2-to-4 times greater than normal during months that floods were reported, regardless of season. Few historical Havasu Canyon floods were associated with unusually large precipitation, either in single or multiday storms (table 3). The July 1992 flood in Havasu Creek was one of the best examples of a flood not associated with unusual rainfall. This fact might reflect the drainage basin's propensity to produce runoff (flashiness), the localized nature of precipitation over the basin, the sparseness of precipitation stations, or a combination of all of the above. In contrast, the 1993 winter flood corresponded with two extreme storms: a large storm with a relatively long recurrence interval that was preceded by an even rarer one-day precipitation burst (table 3). The three-day storm ranked number one in the Williams record, while the one-day burst ranked number two.

PHOTOGRAPHIC EVIDENCE OF FLOOD DAMAGE IN HAVASU CANYON

Owing to its scenery, the travertine pools, waterfalls, and riverine environment of Havasu Canyon have been photographed repeatedly since the late 19th century. From 1991 through 1995, 82 historical photographs of Havasu Canyon were examined, and 56 were replicated (fig. 18; appendix 2), to document the effects of floods on riparian vegetation, waterfalls, and travertine pools. Photographs considered historical (those taken before the 1990 flood) were taken from 1885 through 1988.

Havasu Canyon Near Supai

Ten photographs showing Havasu Canyon near Supai were examined, but only one was replicated (fig. 18; appendix 2). These photographs show the creek in 1885, about 1899-1900, 1910, 1941,1988, and 1991. The pre-1910 photographs show Havasu Canyon nearly devoid of trees although a dense, riparian-plant community of unknown species lined the creek. Because Supai was upstream from its present site until 1910 (fig. 1c) the pre-1910 views show the creek before the impacts of agriculture.

The 1941 view shows different conditions in this section of Havasu Canyon. After the relocation of Supai in 1910, the bottomland near the new townsite was farmed extensively. By 1941, the creek was lined with cottonwood and ash trees despite the floods that occurred before 1935. Dense forests on the bottomland suggest that floods just before 1941 were relatively small or that the channel had a large conveyance.

Photographs taken before and after the 1990 flood (fig. 19) show some effects of the 1990 flood in this section of Havasu Canyon. In 1988, trees of approximately the same height as those present in 1941 lined the creek. In 1991, the channel appeared scoured, but most of the trees survived the 1990 flood. Comparison of the 1941 and 1988 views show that agricultural activities have decreased on the bottomlands near Supai. Interpreting channel changes from these five photographs is difficult, owing to human impacts following relocation of the village in 1910. The photographs taken around the turn of the century, however, stand in contrast with later views because mature trees are missing from the channel banks. The absence of large trees may reflect the damage caused by the large floods before 1899 or may be caused by some unknown activities of the Havasupai.

Fiftyfoot Falls

The first waterfall in Havasu Canyon, Fiftyfoot Falls, is about 2 km downstream of Supai (fig. 1c). Historical accounts suggest that this waterfall, which originally was known as Supai Falls, formed by a flash flood from an unnamed tributary in 1932 (Granger, 1960); however, Fiftyfoot Falls is the subject of an 1885 photograph. Although four photographs of Fiftyfoot Falls were found, taken in 1885, 1937, 1946, and 1970 (fig. 18; appendix 2), none could be accurately replicated owing to extensive channel changes.

The replicate photographs show that Fiftyfoot Falls has been the most unstable waterfall in Havasu Canyon during the last 110 years. Joseph Muench (written commun., 1991), who took a 1937

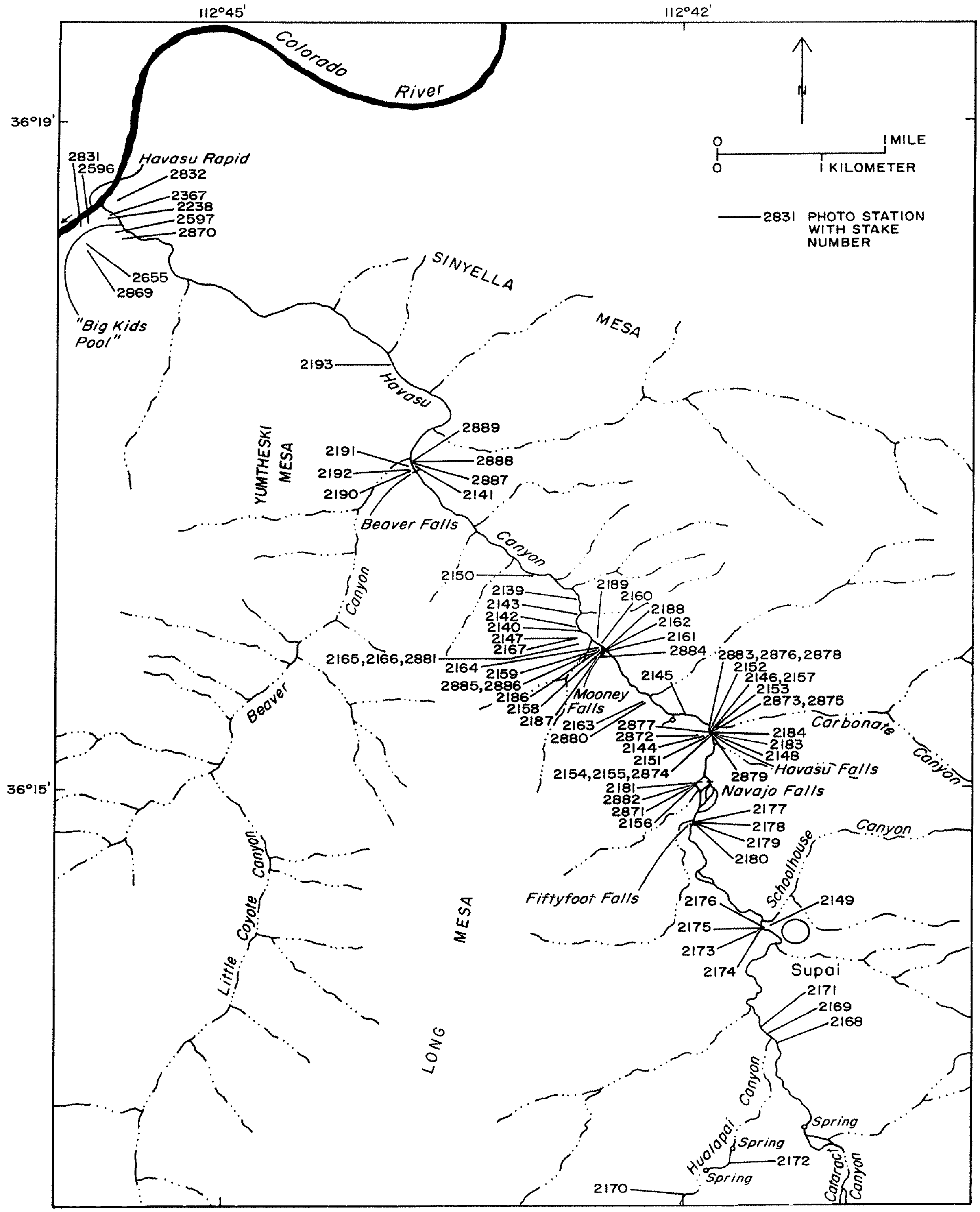
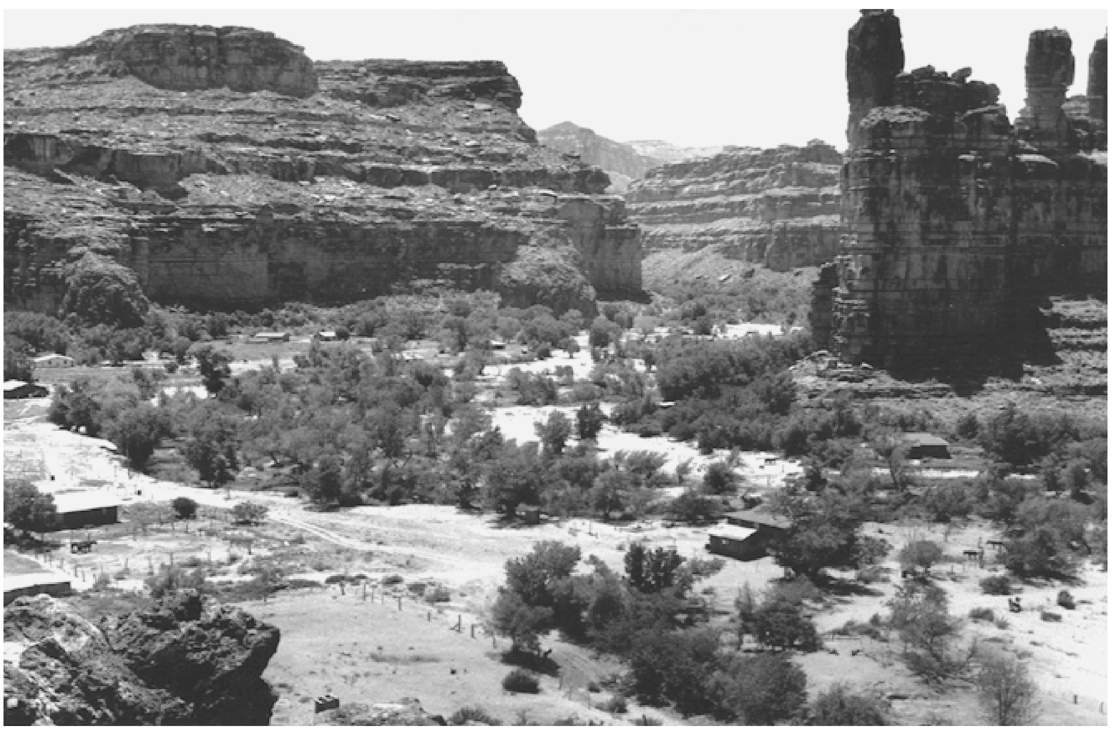


Figure 18. The locations of camera stations for historical photographs of Havasu Canyon. Stake number refers to the permanent record number of the repeat photographs at the Desert Laboratory, Tucson, Arizona.

A. 1988



B. 1991

Figure 19. Replicate views of Havasu Canyon in the vicinity of Supai. A, (1988). View of Havasu Canyon near Supai before the 1990 flood (Brownold). B, (1991). Replicate view showing the effects of the 1990 flood on Havasu Canyon near Supai (Stake 2149).

photograph of Fiftyfoot Falls, stated that it was a prominent feature in 1937; the waterfall had been completely destroyed by floods before his return in 1939. In 1970, George Billingsley (U.S. Geological Survey, oral commun., 1994) observed that headward erosion and channel avulsion significantly changed Havasu Creek near Fiftyfoot Falls. On the basis of these accounts, Fiftyfoot Falls was removed and reformed in only 32 years. Whether the waterfall photographed by Muench in 1937 is the same one photographed in 1885 was impossible to determine. From its appearance in historical photographs, and the reported magnitude of the 1910 flood, Fiftyfoot Falls was destroyed and reformed at least once between 1885 and 1937. Photographs of Fiftyfoot Falls taken in 1946 and 1970 also show differences in comparison to earlier photographs. Because the canyon is wide immediately downstream from Supai, it is possible that waterfalls rapidly form and degrade in this reach depending on the influence of riparian vegetation, travertine deposition, and erosion caused by floods.

Changes in the appearance of Fiftyfoot Falls cannot be associated with specific 20th-century floods, but instead may reflect the combined effects of headward erosion caused by several floods. During the 1910 flood, an arroyo formed and cut to a depth of about 9 m through the alluvial bottomland upstream of Havasu Falls (fig. 20). This arroyo contributed to the erosion of Fiftyfoot Falls (fig. 1c) during floods after 1910. Until the arroyo channel completely adjusts to the new base level at the top of Havasu Falls, travertine deposits in the vicinity of Fiftyfoot Falls may continue to be unstable. Additional headward erosion of this arroyo occurred during the 1990s flooding. Owing to the fragile nature of travertine deposits between the village and Havasu Falls, future flooding may cause the arroyo to migrate upstream of Supai, posing an additional threat to agricultural lands.

Navajo Falls

Navajo Falls was historically described as the second waterfall downstream from Supai (fig. 1c) before the erosion of Fiftyfoot Falls. A series of six photographs of this waterfall were taken from about 1899 through 1994 (fig. 18; appendix 2). These photographs show large changes in the density and height of riparian vegetation growing along the creek channel upstream of Navajo Falls over about a 95-year period. In contrast, the location and morphology of Navajo Falls has changed only slightly, probably owing to control of the waterfall by Redwall Limestone, while the arroyo now deflects part of the flow eastward through travertine deposits and alluvium, away from Navajo Falls.

A photograph of Navajo Falls taken around 1899 (fig. 21a) shows small trees along the right side of the channel, whereas the left bank and center of the channel had little vegetation. The 1991 replicate (fig. 21b) shows an increase in both the density and height of riparian vegetation. A dense gallery of trees had become established sometime after the turn of the century and was prominent in 1991. A view of the top of Navajo Falls taken in late January, 1910 (fig. 22a) shows the reach upstream was mostly devoid of trees immediately after the 1910 flood, which contrasts greatly with the circa 1899 view (fig. 21a). The 1910 view also shows that significant incisional erosion occurred between about 1899 and 1910, probably a result of the 1910 flood. The 1994 match (fig. 22b) shows fewer and smaller trees at the top of the waterfall than in 1910; most trees in 1994 were 10 to 15 m tall.

Photographs taken in 1941 and 1970 (appendix 2) show dense riparian vegetation above and below Navajo Falls. Denser riparian vegetation seen in both 1941 and 1970 likely means that frequent, large floods around the turn of the century prevented establishment of vegetation near Navajo Falls. Floods from 1990 through 1993 had little impact on riparian vegetation upstream of Navajo Falls.

Havasu Falls

Havasu Falls, the second highest waterfall in Havasu Canyon, is just downstream of Navajo Falls (fig. 1c) and is one of the most frequently photographed features in Grand Canyon. Numerous photographs that show the waterfall and its plunge pools (fig. 18; appendix 2) provide information on the effects of large floods in Havasu Creek after 1885; 34 historical and replicate photographs of Havasu Falls taken in 1885, circa

Figure 20. (1990). View of the arroyo formed between Havasu and Fiftyfoot Falls after 1910 (Crumbo, Stake 2197).

1899-1900, 1903, 1905, 1907, 1911, 1937, 1947, 1968, 1970, 1988, 1991, and 1994 were examined (appendix 2).

The earliest images of Havasu Falls, taken in June 1885, show a very different waterfall than the one that appears in photographs taken after 1910 (fig. 23a). The 1994 match of the 1885 view (fig. 23b) shows a notch that is incised about 9 m into the top of Havasu Falls. This notch appears in all photographs taken after 1910, and is attributed to the 1910 flood (Kolb, 1914; Griffith, 1963), based on photographs taken by Barnes in late January 1910 (appendix 2). Although pools below the falls are obscured in the 1994 view, the modern plunge pool is considerably smaller than the one shown in any of the 1885 views. The sites where riparian trees were established above and below Havasu Falls have changed greatly during the last 110 years because of channel avulsion, natural mortality, and changes in travertine deposits.

A photograph taken sometime around 1899 (fig. 24a) reveals that the notch at the top of Havasu Falls did not exist before the turn of the 20th century, and that the large plunge pool in the 1885

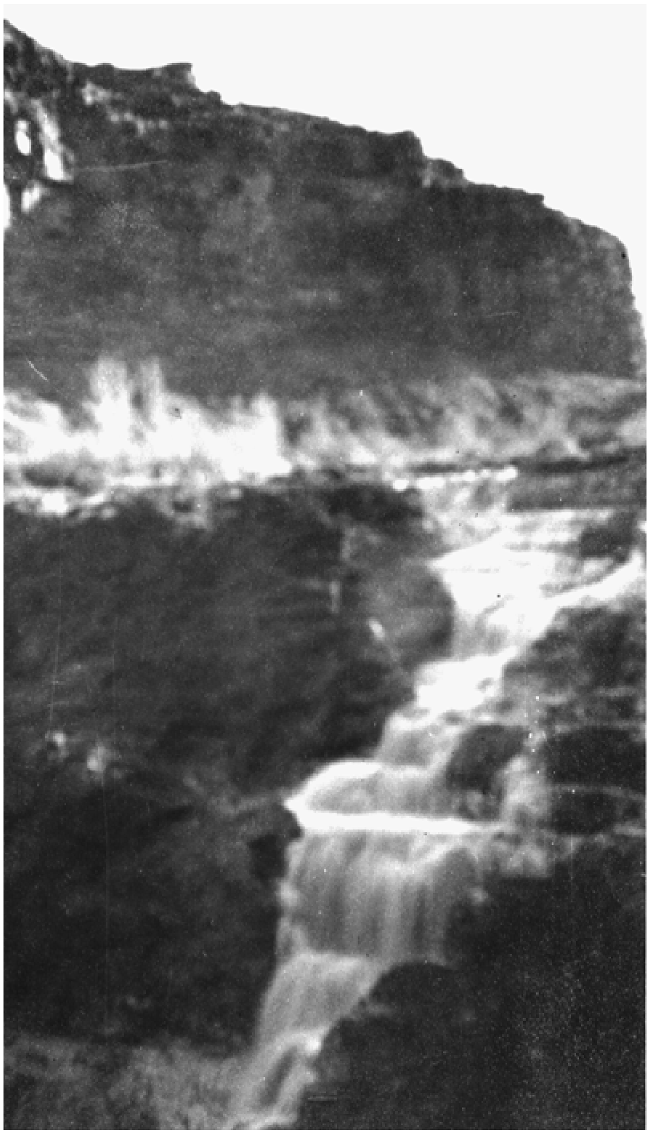
A Kolb 1907 photograph of Havasu Falls is the last known to have been made before the 1910 flood occurred (fig. 26a). Its 1994 replicate (fig. 26b) again shows the deeply incised notch formed during that flood. Erosion of the notch in Havasu Falls in 1910 is best shown from near the top of the waterfall (fig. 27) looking downstream. Large cottonwood trees present below the waterfall occurred further downstream in 1907 than they did in 1994.

Perhaps the most revealing photograph of Havasu Falls was taken in 1905 (fig. 28a). The travertine-controlled plunge pool below the waterfall had been partially destroyed by 1905, possibly by the 1899 flood and (or) the 1905 flood, but the broad lip of the waterfall was intact. The 1905 photograph also shows large trees present about 50 m downstream from the waterfall; in contrast, the 1994 replicate (fig. 28b) shows large cottonwood trees closer to the base of the waterfall than in 1905. The pool beneath the waterfall apparently reformed after 1905, possibly during the period of reduced flood frequency between 1935 and 1990.

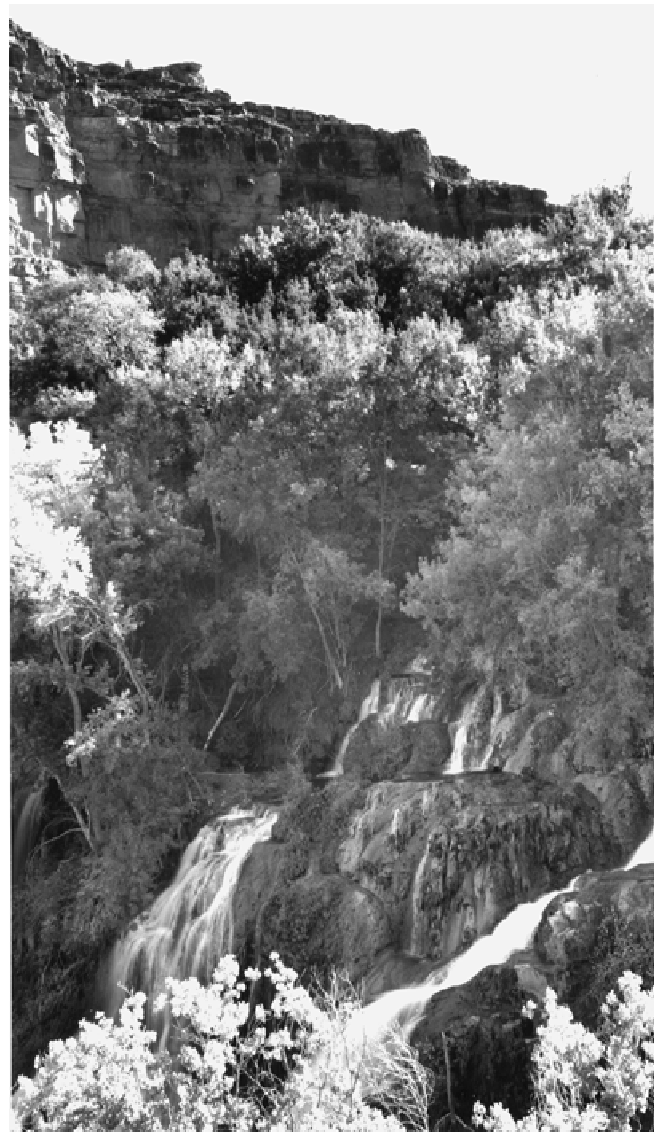
A. 1899

B. 1991

Figure 21. Replicate views of Navajo Falls. A, (ca. 1899). View of Navajo Falls and riparian vegetation along Havasu Creek before the 1910 flood (Peabody).   B, (1991). Replicate view showing Navajo Falls and riparian vegetation along the creek after the 1990 flood (Stake 2156).



A. 1910



B. 1994

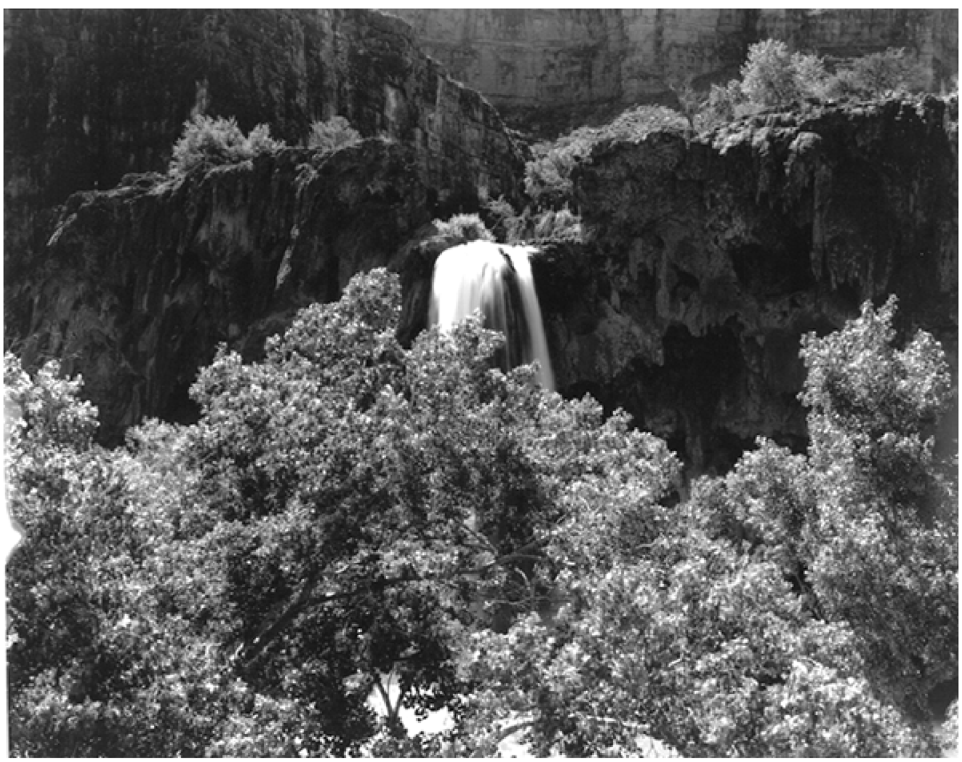
Figure 22. Replicate views of Navajo Falls. A, (1910). View of Navajo Falls and riparian vegetation along Havasu Creek immediately after the 1910 flood. The photograph is out of focus, but shows the scouring effects of the flood (Barnes). B, (1994). Replicate view showing Navajo Falls and riparian vegetation along Havasu Creek after the 1990s floods (Stake 2871)

A. 1885

B. 1994

Figure 23. Replicate views of Havasu Falls. A, (1885). View showing Havasu Falls and its plunge pool before erosive historic floods (Wittick). B, (1994). Replicate view showing Havasu Falls, its plunge pool, and riparian vegetation after the 1990s floods (Stake 2875)

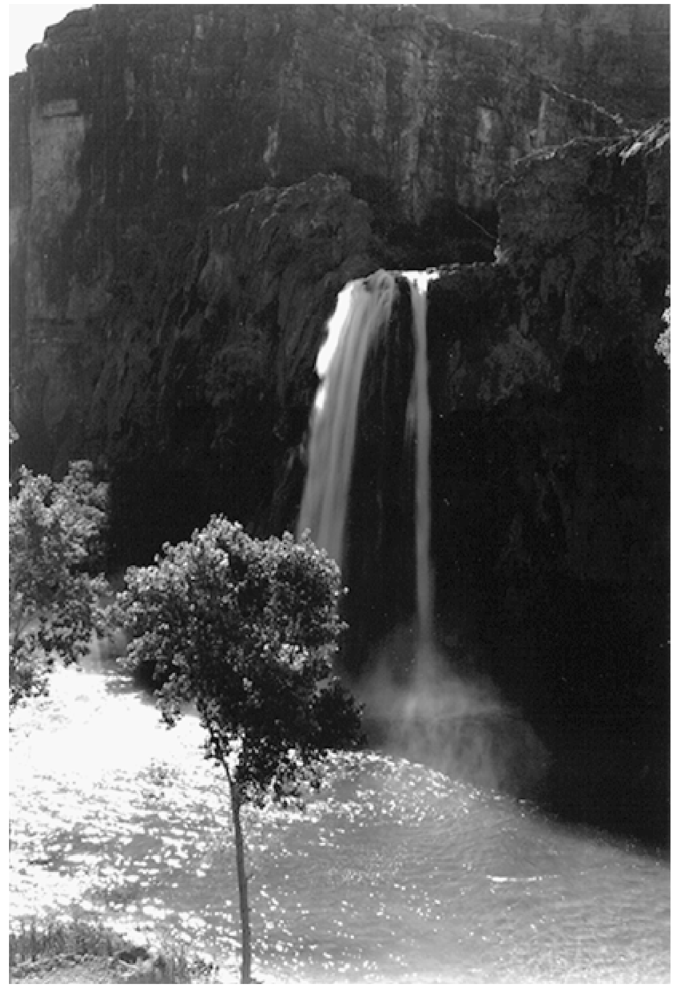
A. 1899



B. 1991

Figure 24. Replicate views of Havasu Falls. A, (ca. 1899). View showing Havasu Falls and its plunge pool before erosion of the top of the waterfall (Peabody). B, (1991). Replicate view showing the erosion of the top of Havasu Falls that occurred in 1910 and the dense growth of riparian vegetation that withstood the 1990 flood (Stake 2153).

A. 1903



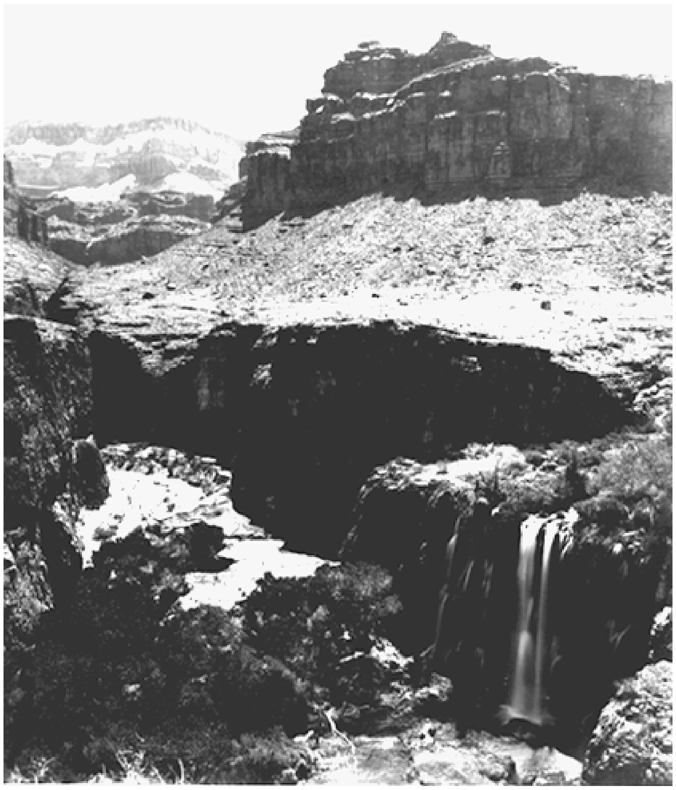
B. 1991

Figure 25. Replicate views of Havasu Falls. A, (1903). View showing Havasu Falls and its plunge pool before the 1910 flood (Marshall). B, (1991). Replicate view showing Havasu Falls, its plunge pool, and riparian vegetation that withstood the flood of September 1990 (Stake 2151).

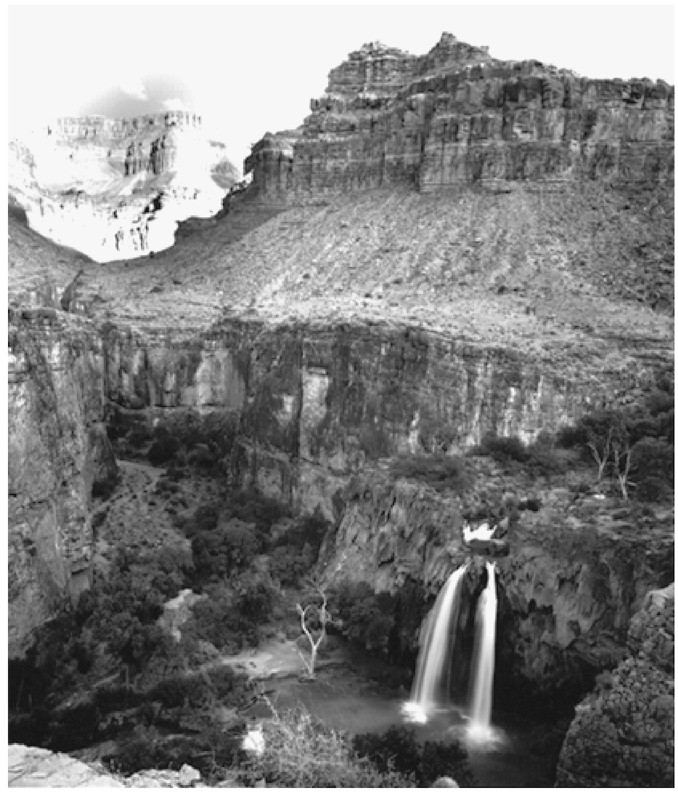
A. 1907 B. 1994

Figure 26. Replicate views of Havasu Falls. A, (1907). View showing Havasu Falls and its plunge pool just before the 1910 flood (Kolb). B, (1994). Replicate view showing Havasu Falls, its plunge pool, and riparian vegetation after the 1990s floods (Stake 2877).

Figure 27. (1994). Downstream view showing the incised notch in Havasu Falls caused by the 1910 flood (Stake 2879). The channel incised about 9 m through travertine deposits.



A. 1903



B. 1994

Figure 28. Replicate views of Havasu Falls. A, (1905). View showing Havasu Falls and the juncture of Havasu and Carbonate Canyons before the 1910 flood (Darton). B, (1994). Replicate view showing Havasu Falls and the juncture of Havasu and Carbonate Canyons after the 1990s floods (Stake 2872).

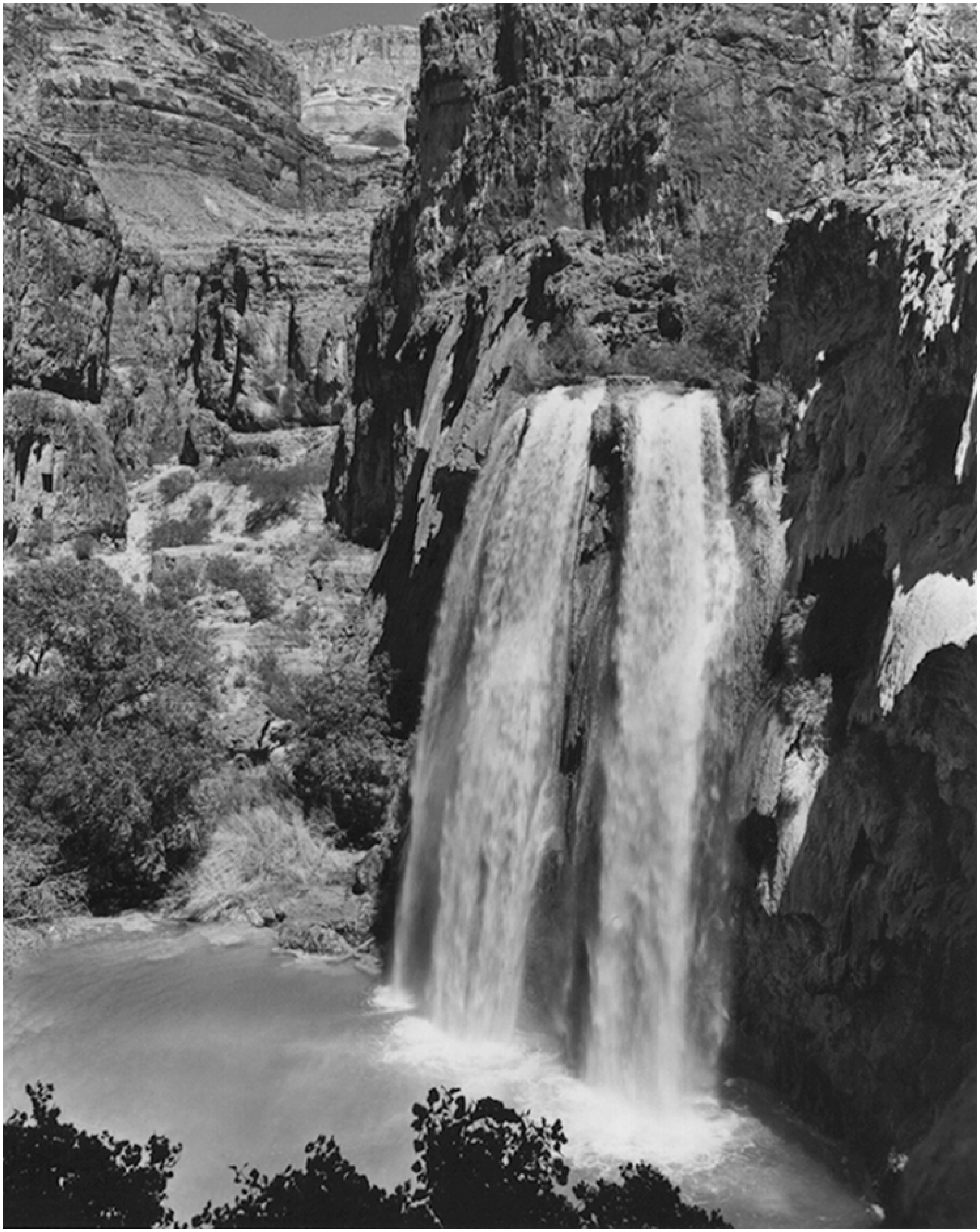


Figure 29. Replicate views of Havasu Falls. A, (1937). View showing Havasu Falls and the reformed plunge pool 27 years after the 1910 flood (Muench).

B, (1991). Replicate view showing Havasu Falls and riparian vegetation growing around its plunge pool after the September 1990 flood (Stake 2155).

Figure 29. Continued.

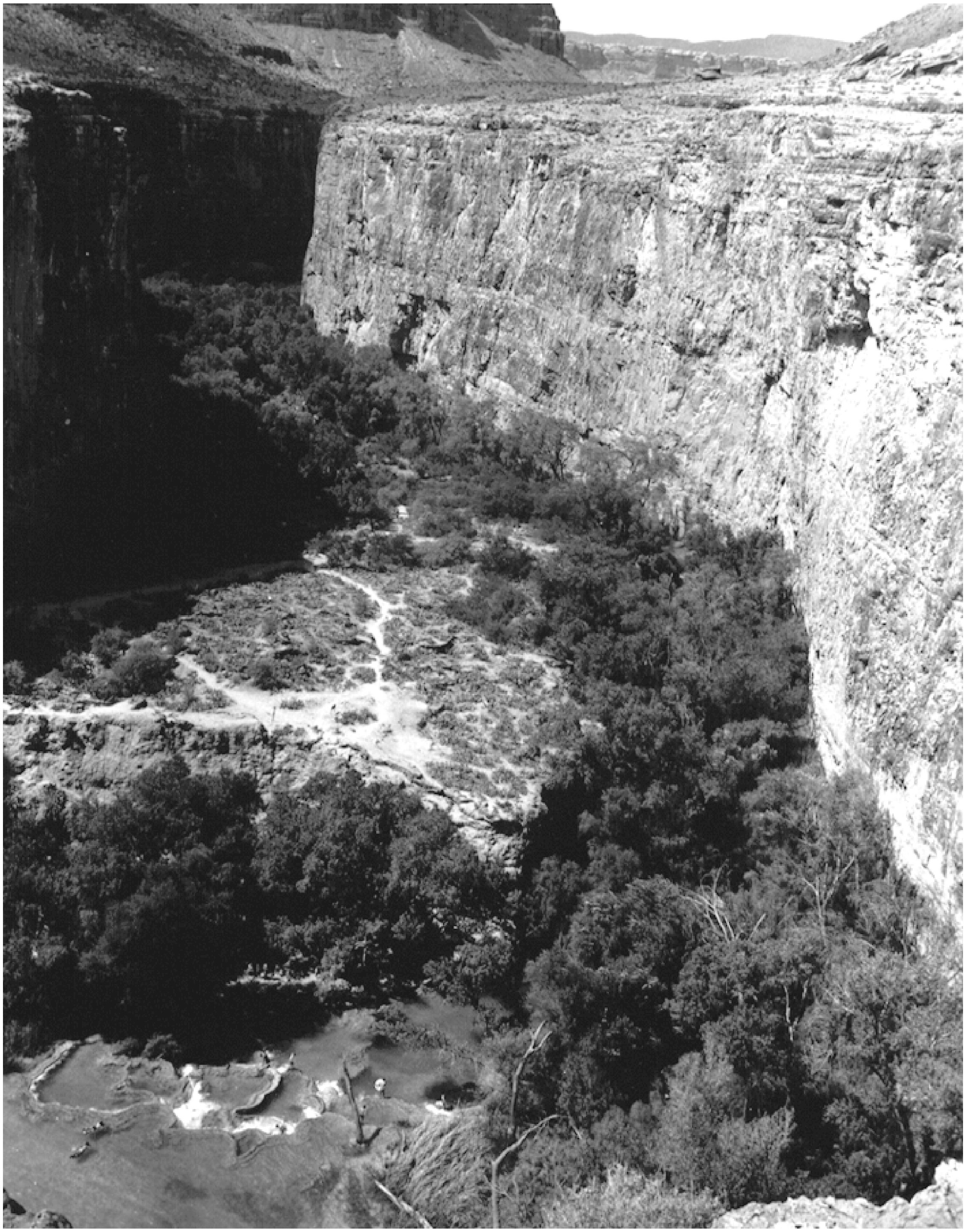
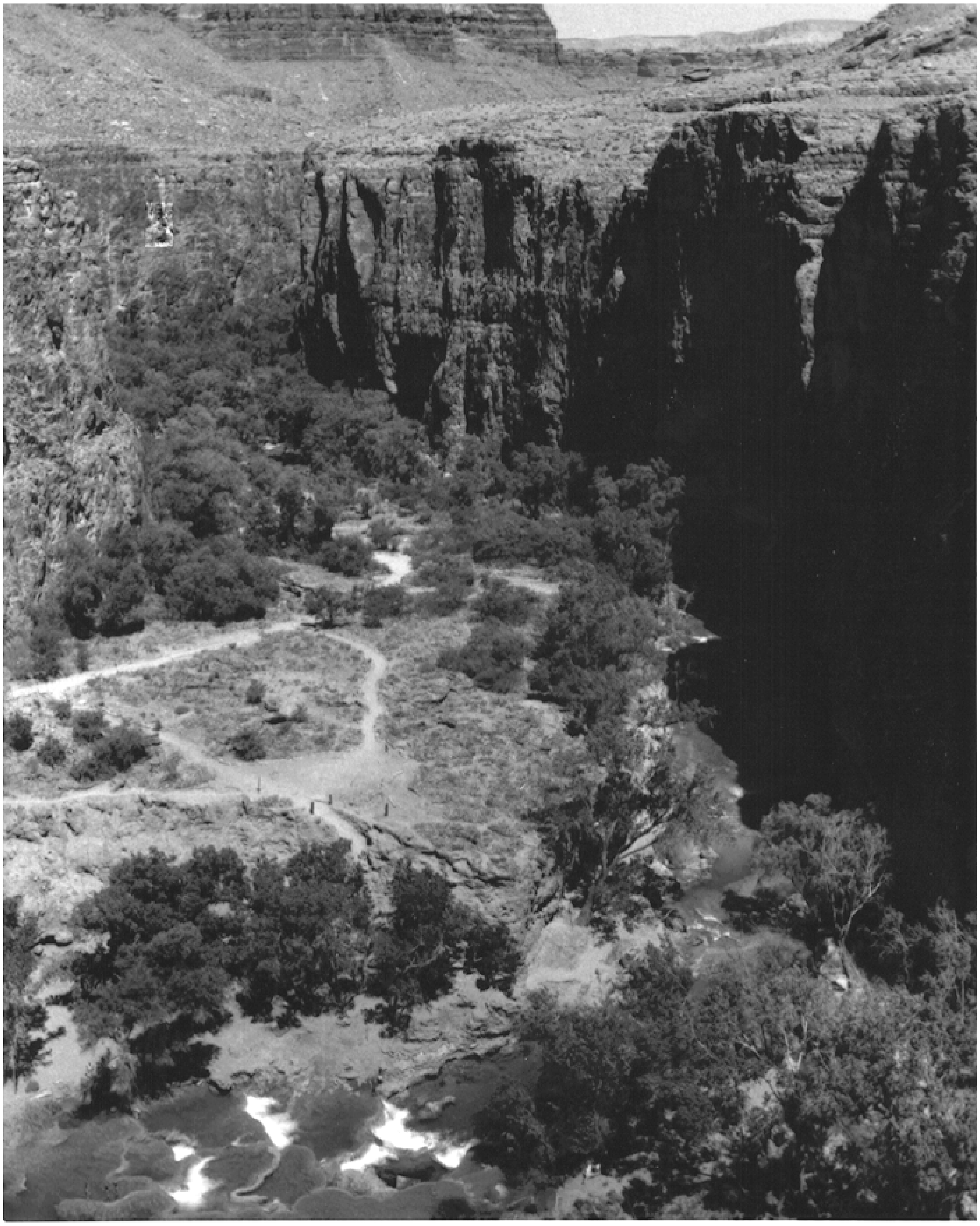


Figure 30. Replicate views of Havasu Canyon downstream from Havasu Falls. A, (1988). View showing Havasu Creek and riparian vegetation immediately downstream from Havasu Falls before the 1990 flood (Brownold).



B, (1991). Replicate view showing Havasu Creek and damaged riparian vegetation immediately downstream of Havasu Falls after the 1990 flood (Stake 2148).

Figure 30. Continued.

The 1905 view also shows large alluvial terraces at the confluence of Havasu and Carbonate Canyons (fig. 1c) that were eroded by flooding after 1905. Eroded remnants of these terraces are present on both sides of the creek below Havasu Falls and formed a large pool 8 to 10 m above the one present in 1994. The plunge pool below Havasu Falls was smaller in 1994 than in 1885. On the basis of the position and size of the partially-eroded travertine deposits examined in 1994 downstream from the plunge pool, a larger pool likely existed before about 1899 like the one seen in the 1885 photographs. The alluvial terraces on the right side of the confluence in the 1905 view apparently were part of this earlier pool. The top of these large travertine dams is about 8 m higher than the elevation of the dam forming the 1994 pool. Photographs showing the base of Havasu Falls from 1885 through 1910 indicate the larger pool was eroded during that period and the channel was deepened by about 1899.

Comparison of a 1937 photograph and a 1991 replicate (fig. 29) shows that Havasu Falls changed very little in the 54-year period. Trees at the base of the waterfall in 1937 were about twice as tall in 1991. This match gives some perspective on the effects of the 1990 flood because most of the modern pool and riparian vegetation that developed after the 1910 flood survived. A 1947 view (appendix 2), similar to the 1937 view, shows almost no change in the waterfall or pool during those 10 years, although Muench reported Fiftyfoot Falls was completely destroyed during the same period. This information supports the conclusion that Fiftyfoot Falls was partially destroyed by headword incision upstream of Havasu Falls that was probably related to small floods.

Replicates of 1968 and 1970 views of Havasu Falls (appendix 2) revealed little change to the waterfall, its pool, or riparian vegetation between 1968 and 1994, despite the 1990s floods. Comparison of Billingsley 1968 and 1970 views with similar ones taken in 1988 (appendix 2) likewise revealed only minor changes to the channel or bottomland vegetation near the waterfall. Comparison of 1988 and 1991 photographs (fig. 30) shows the impact of the 1990 flood on the pools and vegetation near Havasu Falls; the erosion in 1990 is much less severe than that seen in 1910. Comparison of these photos also show that small travertine dams deposited in the notch after 1910 were eroded during the 1990 flood, resulting in more-channelized flow at the top of Havasu Falls. In addition, several trees growing in the creek channel at the top of the waterfall were destroyed by the 1990 flood.

On the basis of timing of channel erosion from 1885 through 1994, the 1990s floods were less erosive at Havasu Falls and presumably smaller than floods from 1899 through 1935. Erosion of the notch at the top of the waterfall and in the channel upstream during the 1910 flood greatly exceeded that of any other 20th century flood. The formation of large pools and establishment of riparian vegetation at the base of Havasu Falls from 1937 through 1988 was possible because of the small floods from 1940 to 1990. The change in channel conditions between 1940 and 1990 suggests a high recovery rate during periods of flood quiescence as short as 50 years.

Havasupai Campground

Eight original and replicate photographs showing the reach between Havasu and Mooney Falls, referred to here as the “Havasupai campground,” were examined for flood-related change (fig. 18; appendix 2). The original images were made in 1903, 1910, and 1988 and were replicated from 1991 through 1994 (appendix 2). The time series represented by these photographs suggests that the Havasupai campground had only slightly less vegetation in 1903 compared to 1994. However, comparison of the 1903 and 1910 views with the 1994 replicates (figs. 31 and 32) indicates that most of the vegetation uprooted from the canyon bottom in 1910 had recovered by 1994 and persisted despite the 1990 and 1993 floods.

In contrast to the erosion apparent in the 1910 view, a replicate pair of 1988 and 1991 views, made about 200 m upstream (fig. 33), showed little vegetation damage or channel change caused by the September 1990 flood. The damaging effects of the 1910 flood (fig. 31), in comparison with minor changes caused by the 1990s floods in the

A. 1910

B. 1994

Figure 31. Replicate views of Havasu Canyon in the Havasupai campground. A, (1910). View showing Havasu Creek in the Havasupai campground immediately after the 1910 flood. The photograph is out of focus, but shows the scoured condition of the channel (Barnes). B, (1994). Replicate view showing Havasu Creek in the Havasupai campground after the 1990s floods (Stake 2883).

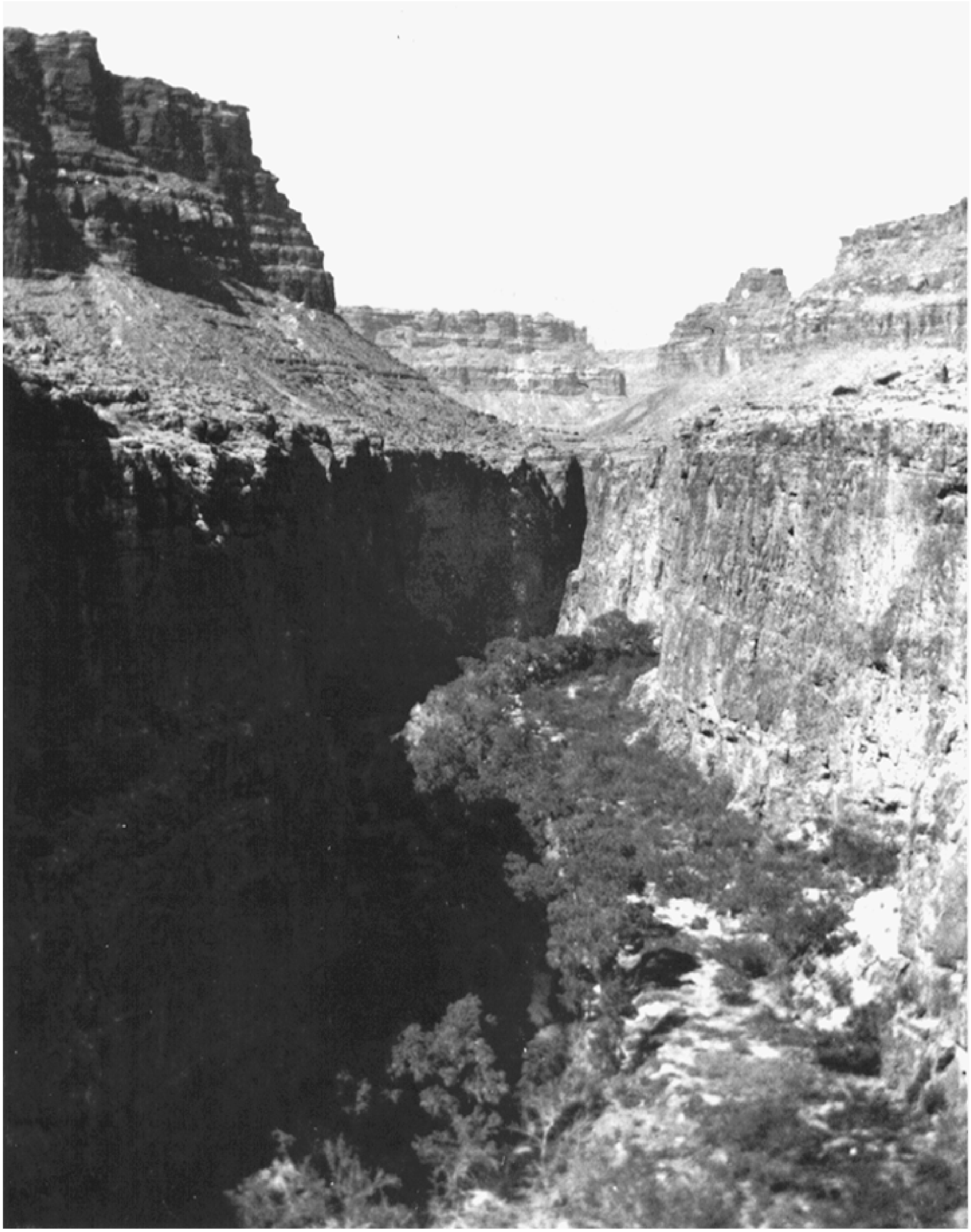
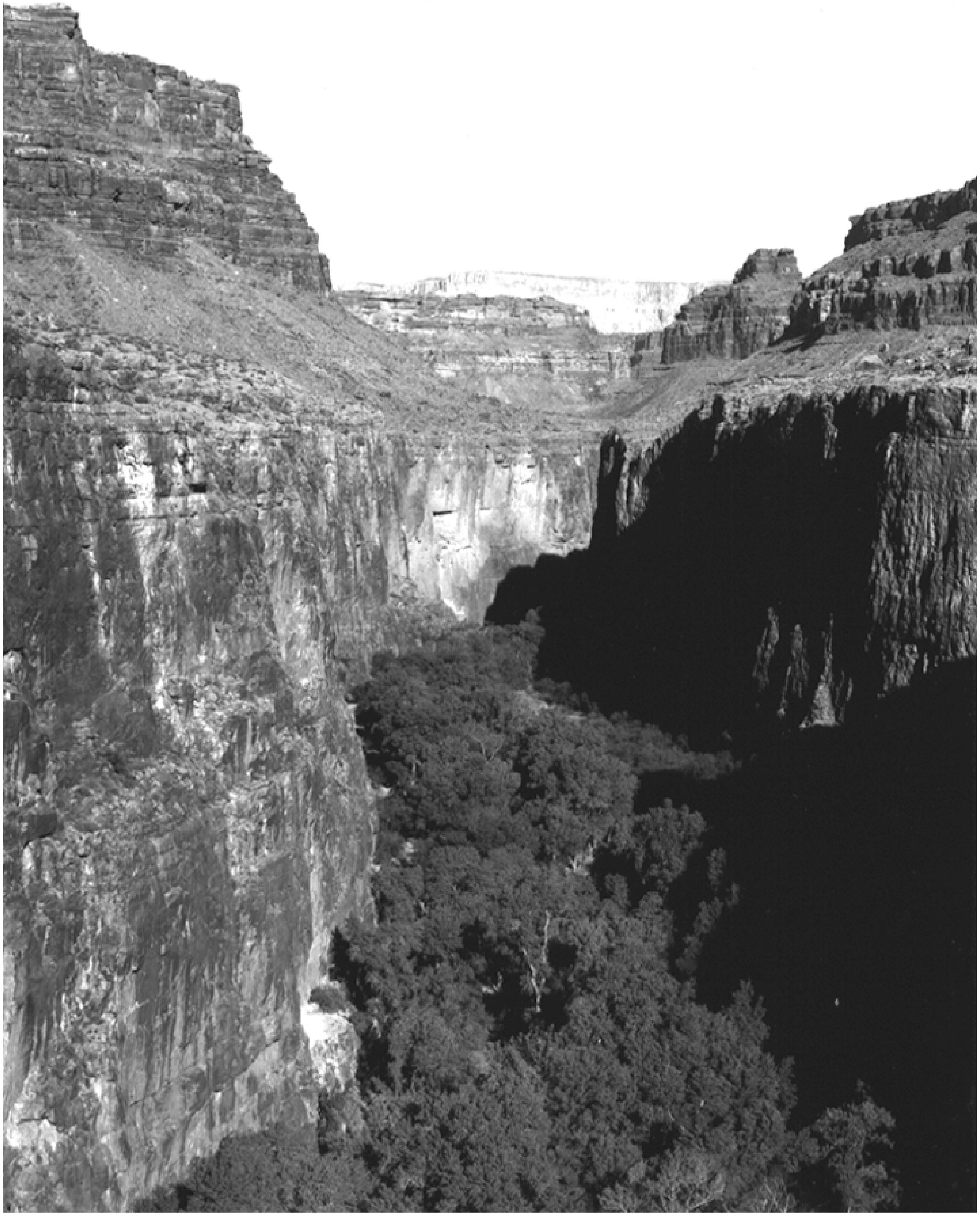


Figure 32. Replicate views of Havasu Creek in the Havasupai campground. A, (1903). View showing Havasu Canyon in the Havasupai campground after the 1899 flood (Marshall).



B, (1994). Replicate view showing Havasu Creek in the Havasupai campground after the 1990s floods (Stake 2880)

Figure 32. Continued.

Havasupai campground reach (fig, 33), supports the conclusion that the 1990 flood was less destructive, and presumably smaller than the 1910 flood.

Mooney Falls

Mooney Falls, the highest waterfall in Havasu Canyon, is immediately downstream from the Havasupai campground and is about 1.6 km downstream of Havasu Falls (fig. 1c). Examination of 28 original and replicate photographs made from 1885 through 1994 of Mooney Falls and vicinity (fig. 18; appendix 2) revealed little change in the waterfall and riparian vegetation over 110 years. Although some erosion of travertine deposits occurred at the top of Mooney Falls, its overall appearance is unchanged. Comparison of an 1885 photograph with its 1994 replicate (fig. 34) shows that the size and locations of trees at the top of the waterfall are very similar. A 1907 view of Mooney Falls and its replicate (fig. 35) also show very little change. Despite 19th-and 20th-century flood accounts in lower Havasu Canyon, no major changes occurred at Mooney Falls during the last century. Comparison of photographs of campground reach taken in 1907, 1910, and their 1991-1994 replicates, further supports the idea of rapid recovery of riparian vegetation upstream of Mooney Falls.

A 1988 view and 1991 replicate of Mooney Falls (fig. 36) shows that the waterfall, its plunge pool, and riparian vegetation upstream were only slightly affected by the 1990 flood. Although large numbers of trees were uprooted in most of Havasu Canyon, the riparian vegetation upstream and downstream from Mooney Falls was not greatly altered. The minimal effects of the 1990 flood in this reach could, in part, be explained by the energy-dissipating effects of Havasu Falls upstream. The wide channel of Havasu Creek through the campground reach also decreases the velocity of flow approaching Mooney Falls. The large plunge pool below Havasu Falls, combined with the wide channel downstream, may protect Mooney Falls from severe erosion.

Mooney Falls to Beaver Falls

Examination of 13 original and matched photographs of Havasu Creek, taken between Mooney Falls and Beaver Falls from about 1899 through 1994 (fig. 18; appendix 2), were notable for showing equivocal amounts of flood disturbance. For example, a circa 1899 image of the channel immediately below Mooney Falls revealed vegetation nearly identical to the 1994 replicate, despite the floods of the 1990s (fig. 37). In contrast, comparison of 1988 views and 1991 replicates (appendix 2) showed variable amounts of disturbance to riparian plants (fig. 38). Channel erosion caused by the three floods in the 1990s occurred only in narrow reaches downstream from Mooney Falls, mostly in 1990. Some locally severe erosion of travertine pools and waterfalls occurred in the narrowest parts of this reach (fig. 39). Contrasting levels of erosion caused by 1990s floods between this reach and the Havasupai campground appear to be related to the presence of waterfalls and wide channels.

Beaver Falls

Beaver Falls is the farthest downstream waterfall in Havasu Canyon (fig. 1c). This waterfall consists of a series of cataracts that are informally referred to as Upper and Lower Beaver Falls. Examination of eleven original and matched photographs of Beaver Falls taken from 1903 through 1994 (fig. 18; appendix 2) revealed that this waterfall has been one of the most unstable features in Havasu Canyon during the 20th century.

A 1988 photograph of the waterfall shows it as it looked before the September 1990 flood (fig. 40a). The 1991 replicate shows changes that occurred during the 1990 flood (fig. 40b). The main impact of the 1990 flood in the vicinity of Beaver Falls was severe damage to riparian vegetation, whereas little change occurred in the travertine waterfall or its plunge pool.

A 1970 view of Upper Beaver Falls (fig. 41a) appeared nearly identical to its 1994 replicate (fig. 41b); showing very little change caused by flooding between 1970 and 1994. A 1937 photograph

A. 1988

B. 1991

Figure 33. Replicate views of Havasu Canyon in the Havasupai campground. A, (1988). View showing riparian vegetation along Havasu Creek in the Havasupai campground before the 1990 flood (Brownold). B, (1991). Replicate view showing the damaged riparian vegetation along Havasu Creek in the Havasupai campground after the 1990 flood (Stake 2145).

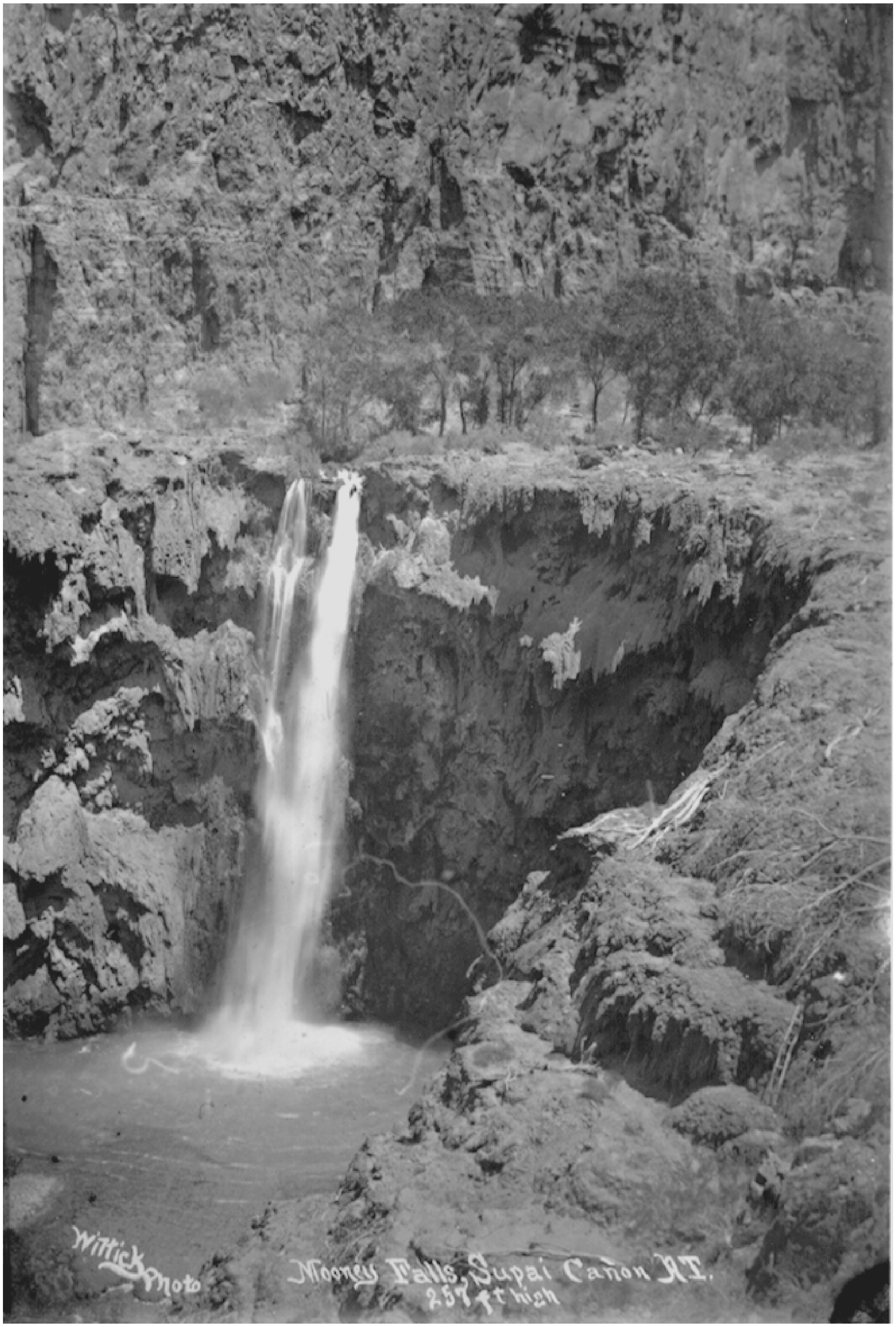
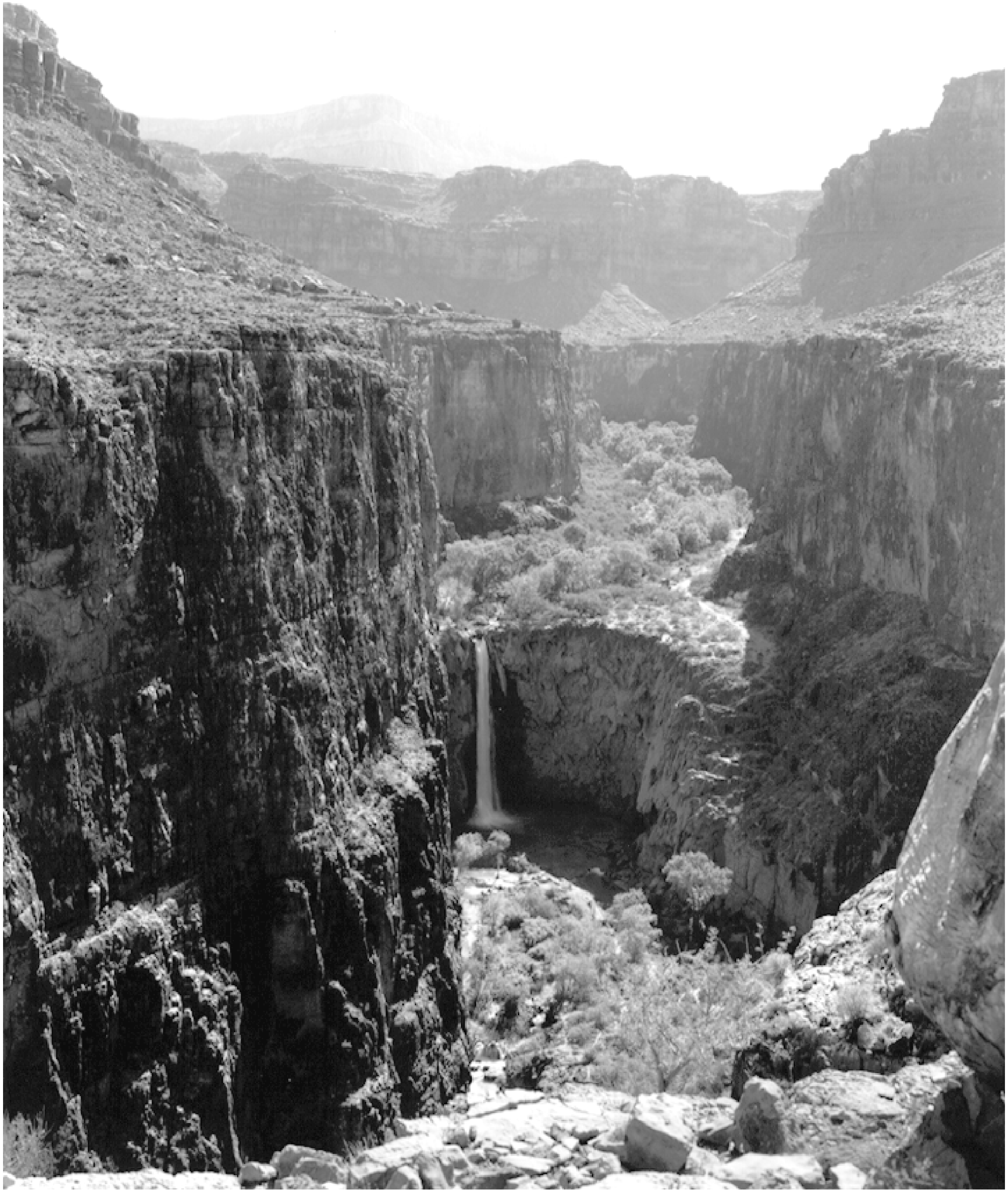


Figure 34. Replicate views of Mooney Falls. A, (1885). View showing Mooney Falls and its plunge pool before the onset of historical floods (Wittick).

B, (1994). Replicate view showing Mooney Falls and its plunge pool after the 1990s floods (Stake 2882).

Figure 34. Continued.

Figure 35. Replicate views of Mooney Falls. A, (1907). View showing Mooney Falls, its plunge pool, and riparian vegetation upstream before the 1910 flood (Kolb).



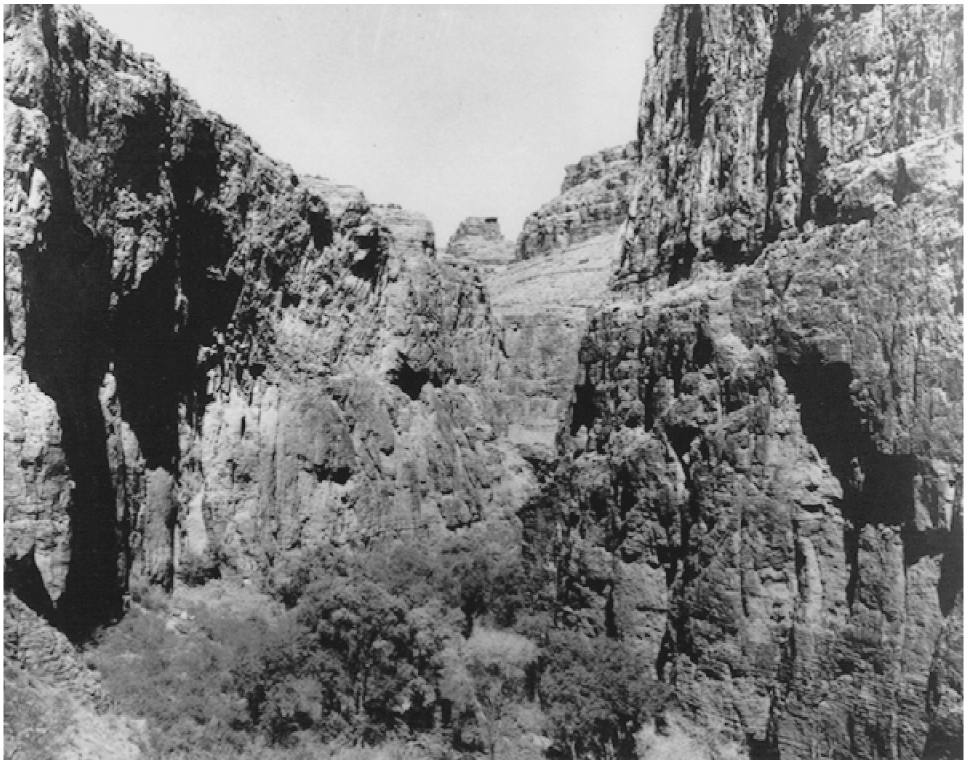
B, (1994). Replicate view showing Mooney Falls, its plunge pool, and riparian vegetation upstream after the 1990s floods (Stake 2881).

Figure 35. Continued.

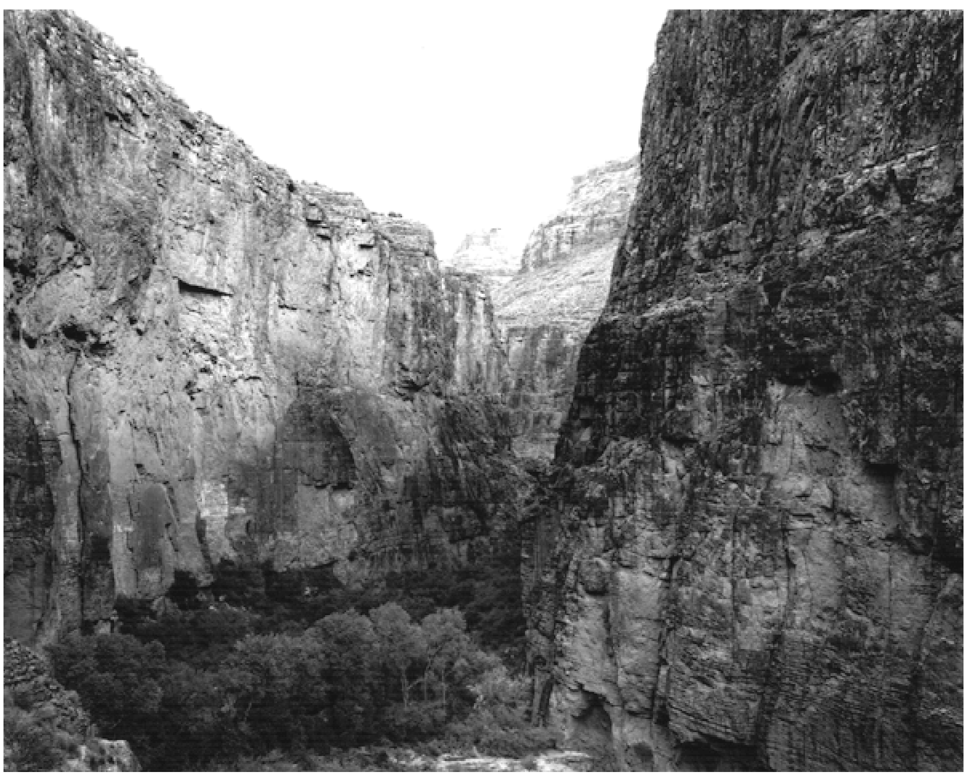
Figure 36. Replicate views of Mooney Falls. A, (1988). View showing Mooney Falls and its plunge pool before the 1990 flood (Brownold).

B, (1991). Replicate view showing Mooney Falls and its plunge pool after the 1990 flood (Stake 2147).

Figure 36. Continued.

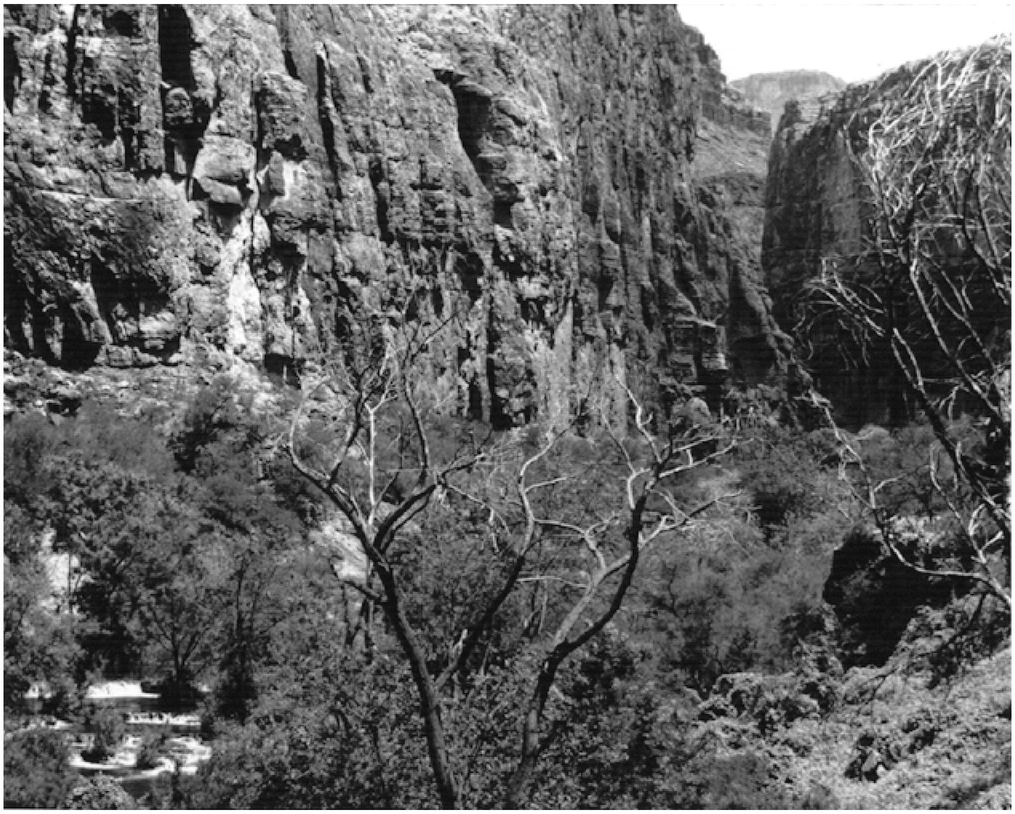


A. 1899



B. 1994

Figure 37. Replicate views of Havasu Canyon downstream from Mooney Falls. A, (ca. 1899). Downstream view showing riparian vegetation along Havasu Creek immediately downstream from Mooney Falls before the 1910 flood (Peabody). B, (1994). Replicate view showing riparian vegetation of Havasu Creek immediately downstream from Mooney Falls after the 1990s floods (Stake 2884).



A. 1988

B. 1991

Figure 38. Replicate views showing riparian vegetation between Mooney and Beaver Falls. A, (1988). View showing riparian vegetation along Havasu Creek between Mooney and Beaver Falls before the 1990 flood (Brownold). B, (1991). Replicate view showing damage to riparian vegetation along Havasu Creek between Mooney and Beaver Falls after the 1990 flood (Stake 2142).

A. 1988

B. 1991

Figure 39. Replicate views near the confluence of Havasu Creek and Beaver Canyon. A, (1988). Downstream view showing travertine deposits near the confluence of Havasu Creek and Beaver Canyon before the 1990 flood (Brownold). B, (1991). Replicate view showing the severely eroded condition of travertine deposits near the confluence of Havasu Creek and Beaver Canyon after the 1990 flood (Stake 2139).

A. 1988

B. 1991

Figure 40. Replicate views of Beaver Falls. A, (1988). Upstream view showing Beaver Falls, its plunge pools, and riparian vegetation along the Havasu Creek channel before the 1990 flood (Brownold). B, (1991). Replicate view showing the scoured condition of Beaver Falls, its plunge pools, and riparian vegetation along Havasu Creek after the 1990 flood (Stake 2141).

A. 1970

B. 1994

Figure 41. Replicate views of Beaver Falls. A, (1970). Upstream view showing Beaver Falls, its plunge pools, and riparian vegetation along Havasu Creek before the 1990s floods (Billingsley). B, (1994). Replicate view showing Beaver Falls, its plunge pools, and riparian vegetation along Havasu Creek after the 1990s floods (Stake 2887).

A. 1937

B. 1994

Figure 42. Replicate views of Beaver Falls. A, (1937). Upstream view showing Beaver Falls and riparian vegetation along Havasu Creek (Muench). B, (1994). Replicate view showing Beaver Falls and riparian vegetation along Havasu Creek after the 1990s floods (Stake 2888).

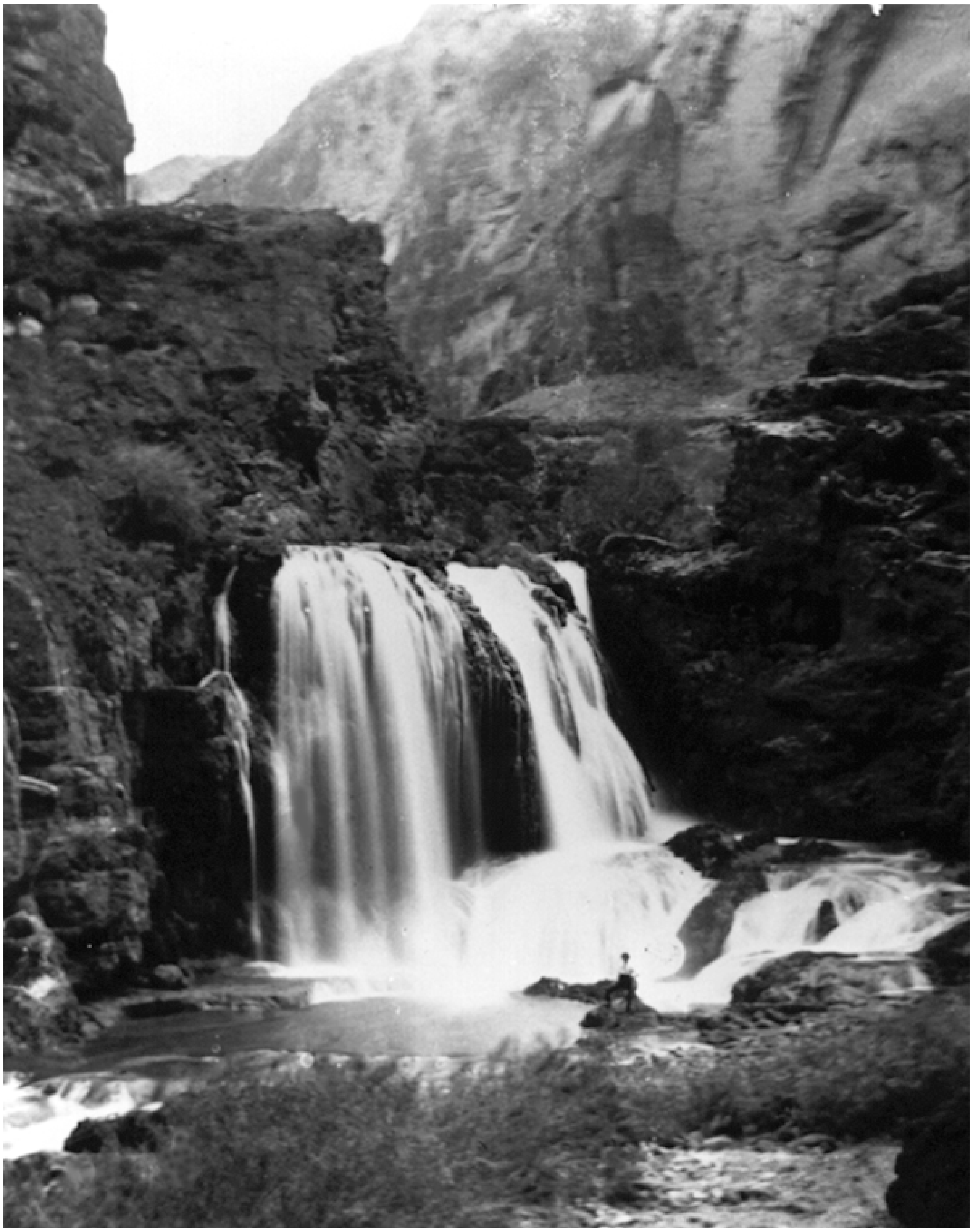


Figure 43. (1903). Upstream view showing Beaver Falls before the 1910 flood (Marshall, Stake 2190).

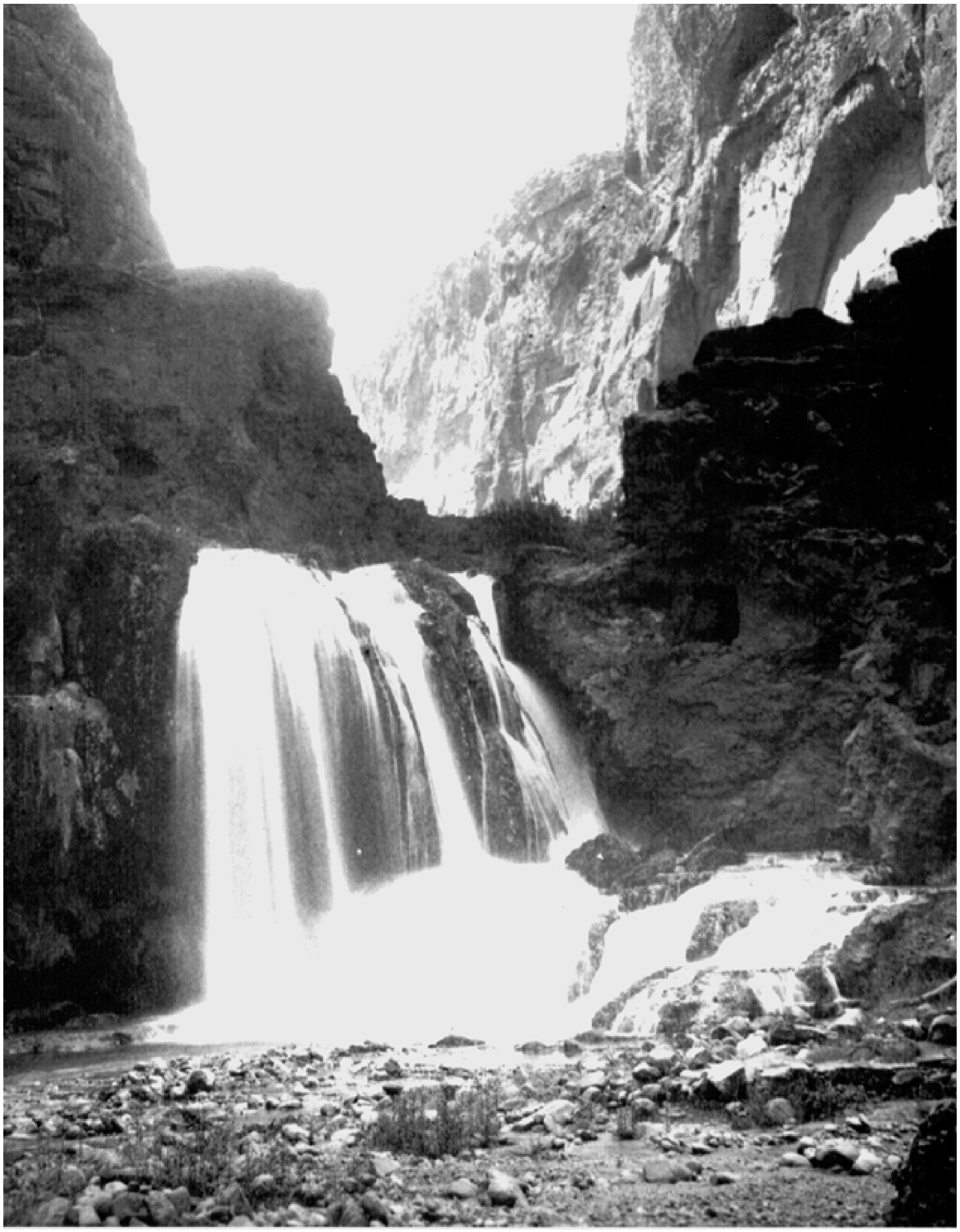


Figure 44. (1907). Upstream view showing Beaver Falls before the 1910 flood (Kolb; Stake 2192).

showing upper and Lower Beaver Falls (fig. 42a), reveals that there was less pool area below the waterfall when compared to the 1994 replicate (fig. 42b). The 1937 view also showed that there was less vegetation in the channel at that time, and that the waterfall was more channelized before the middle of the 20th century.

It was impossible to match the earliest photographs of Beaver Falls, because of extensive channel changes that occurred sometime after 1907 (presumably in 1910). Photographs showing Upper Beaver Falls in 1903 and 1907 showed a waterfall that is nearly unrecognizable when compared with similar images taken in 1937, or later (figs. 41-42). The 1903 view shows a relatively high waterfall with a bi-level plunge pool at its base, and a small secondary travertine dam downstream (fig. 43). The 1907 image, taken from nearly the same place, shows a very similar waterfall (fig 44). A fresh-looking sediment deposit in the 1907 photograph suggests flooding sometime between the times that these two views were made most likely indicating the effects of the 1904-1905 floods. However, the travertine forming the top of the Beaver Falls seen in both of these early views is virtually unchanged.

An approximate match of a 1903 view showing lower Beaver Falls from channel-right showed the most dramatic change of any photograph replicated in Havasu Creek during this study (fig. 45). The 1994 replicate shows that the lower waterfall was completely eroded sometime after 1903-1907, and that the creek channel has since eroded down to an elevation 10 to 15 m below its former bed. The exact timing of this change could not be determined, but the 1910 flood is the most likely cause. Overall, Beaver Falls was probably unchanged from 1903 to about 1910 on the basis of photographs and historical accounts of floods, but changed dramatically owing to floods from 1910 through about 1940. Photographs of the waterfall taken from 1937 through 1994 indicate that Beaver Falls was rebuilt. The waterfall continued to change after 1940, but not as dramatically as during the first third of the 20th century.

Beaver Falls to the Colorado River

Three photographs showing the reach downstream from Beaver Falls before 1940 (fig. 18; appendix 2) were replicated. A 1937 photograph, looking upstream from a point about 3 km upstream from the Colorado River (appendix 2), revealed that this reach contained less riparian vegetation than was present in 1994, despite damage caused by the 1990 flood. However, large boulders and travertine deposits were significantly changed. Comparison of 1923 photographs and their replicates taken in 1991 and 1994 showed more travertine pools after the 1990 flood than had existed 68 years before (appendix 2). Most of the large boulders present in 1923 were still present (fig. 46), which confirms the accounts of river runners who visited the canyon in the 1950s (R. Rigg, 1950s-era river runner, written commun., 1994).

The Confluence of Havasu Creek and the Colorado River

Seven photographs showing the confluence of Havasu Creek and the Colorado River from 1885 through 1947 (fig. 18; appendix 2) were replicated and examined for changes. The earliest views, taken in 1885, were made during high discharge in the Colorado River and were of limited use for interpreting changes in the mouth of the creek. A 1911 photo showed the confluence at low river discharge (fig. 47a); cobbles and boulders were strewn downstream in the Colorado River, but the debris fan was smaller than the one present in our 1993 match (fig. 47b). Comparison of these photographs indicates that the head of Havasu Rapid was in the same location in 1911 as in 1994, but contained more boulders in 1994. The boulders present in 1911 were probably deposited by the 1910 flood and were likely removed by Colorado River floods, particularly the 1921 flood of 6,200 m^3/s (Garrett and Gellenbeck, 1991). A 1947 photograph of the Havasu Canyon confluence (appendix 2) shows no debris fan despite the fact that the stage in the Colorado River is lower than in the 1911 or 1923 views. The debris fan documented in the 1994 match was deposited during the 1992 and 1993 floods (appendix 2).

From this photographic time series, coarse sediment deposited at the head of Havasu Rapid in 1910 was reworked by river floods between 1911 and 1990. Cobbles and boulders were not commonly seen here during the middle part of the

A. 1903

B. 1994

Figure 45. Replicate views of channel erosion of Havasu Creek downstream from Beaver Falls. A, (1903). Upstream view showing Havasu Creek immediately downstream from Beaver Falls before the 1910 flood (Marshall). B, (1994). Replicate view showing severe channel erosion in Havasu Creek immediately downstream from Beaver Falls after the 1990s floods (Stake 2889).

A. 1923

B. 1994

Figure 46. Replicate views of Havasu Creek near its confluence with the Colorado River. A, (1923). Upstream view showing Havasu Creek just upstream from the Colorado River after early historical floods (LaRue). B, (1994). Replicate view showing Havasu Creek just upstream from the Colorado River after the 1990s floods (Stake 2870).

20th century. However, with the onset of large floods in 1990, coarse-grained debris were again deposited at the confluence.

Summary of Photographic Evidence

By examination of 142 photographs of Havasu Canyon, it was concluded that erosion of waterfalls and plunge pools, combined with uprooting or damage to riparian vegetation, occurred during frequent large floods from 1899 through 1935 and from 1990 through 1993. Stable travertine deposits and establishment of dense riparian vegetation after about 1940 agreed well with conclusions from other historical accounts, and suggested that smaller floods occurred between 1935 and 1990. Erosion of travertine deposits and destruction of riparian vegetation was less severe during the 1990 flood than during floods from 1899 to around 1940 (table 3).

Because the travertine deposits and waterfalls are eroded and riparian vegetation is damaged or destroyed by floods, the historical photographs document the persistent effects of floods, including breaching and incision of travertine dams and waterfalls, alteration or draining of pools, and changes in the density of riparian trees. Frequent and (or) large floods cause persistent disturbances that promote establishment of new bottomland growth and new deposits of travertine dams and pools, but floods may prevent establishment of mature plant communities. During periods dominated by small floods, well-developed pools form along the creek channel and the riparian vegetation becomes dense and contains numerous large trees.

Although the Havasupai harvested wood for fuel, they traditionally avoided harvesting trees downstream from Havasu Falls owing to the difficulty of transporting wood upstream to the village. The area downstream of Mooney Falls was also avoided because it was the tribal burial ground before 1900 (Dobyns and Euler, 1971). Recently-increased tourism also has impacted riparian vegetation through indiscriminate woodcutting and trampling. Human impacts along the creek peaked during the late 1960s and early 1970s, but are now minimized owing to stricter camping regulations. According to the combined photographic and historical written record of lower Havasu Canyon, floods were probably the main source of disturbance to the riparian plant community before 1965, particularly downstream from Mooney Falls. Changes in the density and height of trees along the creek apparent in historical photographs mostly reflect periods of large floods or persistent flood quiescence (table 3).

DENDROCHRONOLOGY OF ASH TREES

Tree-ring studies have been used to augment and extend historical, stream-gage, and flood records using tree species similar to those present in Havasu Canyon (Alestalo, 1971, Yanosky, 1983; Hupp, 1988). The tree-ring studies reported here were designed to supplement and test conclusions regarding historical changes in flood frequency derived from historical sources and repeat photography. The short life span of most trees in Havasu Canyon, combined with other biological or direct human influences on the riverine ecosystem, limit the usefulness of the tree-ring data for Havasu Canyon. Nevertheless, the dendrochronological record provides valuable information on the response to flooding and recovery rate from flood damage of riparian trees.

Response Of Riparian Trees To Flooding

The perennial streamflow in Havasu Creek supports a diverse riverine ecosystem (Deaver and Haskell, 1955). Dense stands of willows, cottonwoods, and ash trees line the stream forming a riparian forest only 25 to 100 m wide along many reaches. In this riparian zone, tree roots are mostly in contact with stream water; at greater distances from the stream, soils are too dry to support phreatophytes, and a desert plant community consisting of mesquite, catclaw acacia, oak, Mormon tea, and canyon redbud is present.

Observations of the effects of the 1990 flood were used as a model of how the riparian forest in Havasu Canyon is affected by flooding. Along reaches where stream power was concentrated, the

Figure 47. Replicate views of the confluence of Havasu Creek and the Colorado River. A, (1911). Upstream view from the left bank of the Colorado River showing the mouth of Havasu Creek immediately after the 1910 flood (Kolb).

B, (1993). Replicate view showing the mouth of Havasu Creek and the head of Havasu Rapid (Stake 2655). The new debris fan was deposited by the 1992 and 1993 floods.

Figure 47. Continued.

Figure 48. Oblique aerial view of the scour zone of Havasu Creek in lower Havasu Canyon between Beaver Falls and the Colorado River caused by the 1990 flood (Crumbo, Stake 2198).

1990 flood completely removed the trees adjacent to the channel. Extensive treeless tracts were created along many narrower reaches (figs. 38b and 48), and most trees were removed by the roots rather than broken along trunks. Root systems in these trees were typically shallow, penetrating less than a meter. Where stream power was lower, riparian trees were not removed, but were instead tipped owing to partial erosion of the alluvium around the tree roots. This flood training of riparian vegetation was a common effect of the 1990 flood; the tipped limbs and trunks sprouted new vertically-oriented growth in the first growing season after the flood. Where significant channel incision occurred during the flood, streamside trees commonly showed drought stress by the next dry season, owing to lowering of the local water table. Because the roots of trees growing along Havasu Creek are mostly shallow, even modest channel incision can cause drought stress and limitation of tree growth.

Some of the riparian trees that remained standing were scarred by flood-borne debris. These impact scars ranged from subtle abrasions to gashes that nearly split the tree. Impact scars were rare, possibly because most tree species growing next to the creek bent under the impact of flood debris. Along stream reaches protected from high-energy flood flow, damage was minimal. No effects were observed in the riparian forest from inundation by floodwaters to depths of 1 m.

Based upon these observations, the Havasu Canyon ash forest was expected to display an age structure reflecting the history of flood disturbances. Large floods were expected to remove substantial areas of the riparian forest; post-disturbance recruitment should have produced large areas of similar-aged trees. Sprouts and scars on surviving trees should also date from the approximate time of large floods.

The 1990 flood created an opportunity to determine the age structure of the riparian forest in Havasu Canyon. Hundreds of trees were swept away by the 1990 flood waters to the Colorado River, where many were deposited on sand bars and channel banks. Radial cross sections at approximate breast height (~1.5 m) from 145 of the trees were collected during the winter of 1990-1991 (appendix 3). Although an effort was made to collect a representative sample of sections from each pile of driftwood, very small sections (less than about 50 mm) were not taken because we could not distinguish them from branches. Trees younger than about 10 years therefore are not sampled; otherwise, the driftwood approximates a random sample of trees subject to moderate flood damage along Havasu Creek.

Most of the destroyed trees were ash (*Fraxinus* sp.), reflecting the dominance of this genus along the Havasu Canyon riparian corridor. No attempt was made to identify the ash cross sections to the species level. However, velvet ash (*F. velutina* Torr. var. *glabra* Rehder) is known to be the most common ash in Havasu Canyon (Deaver and Haskell, 1955); other species include single-leaf ash (*F. anomala* Torr.), Lowell's ash (*F. lowellii* Sarg.) and flowering ash (*F. cuspidata* Torr. var. *macropetala* (Eastw.) Rehder). Lesser amounts of willow (*Salix* sp.) and Fremont cottonwood (*Populus fremontii*) were also found. Only the ash trees received further study. Our results are simple ring counts, presumably of annual rings. Attempts to crossdate the samples using standard dendrochronological techniques failed, even though ash trees from other regions, such as the eastern United States (Yanosky, 1983), typically crossdate. The failure of Havasu ash to crossdate may reflect an ecological setting where water is not seasonally limited (*i.e.*, complacent rings; Stokes and Smiley, 1968). Meteorological phenomena such as heavy snow or severe, unseasonable frosts believed to cause crossdating in other non-water limited settings do not occur frequently in the sheltered, mild climate of Havasu Canyon. The poor radial uniformity of many specimens contributed to the crossdating problems; it was not unusual for increment cores taken from the same tree to crossdate weakly or not at all.

Because it was not possible to crossdate the ash samples, the presence of false annual rings or missing annual rings could not be fully evaluated. Ash from the Potomac River Basin in the eastern United States exhibit false annual tree rings or "flood rings" caused by flooding (Yanosky, 1983). Although a careful search was made, flood rings were not identified in ash samples from Havasu Canyon. In the Potomac Basin, the flood rings are caused by defoliation owing to inundation by spring floods. The defoliation causes latewood-like growth to occur in the cambium. Because flooding on the Potomac typically occurs well before the cessation of earlywood formation, the "pseudo-latewood" is followed by more earlywood as the defoliated trees regrow leaves; this phenomenon is unlikely to occur in Havasu Canyon. All recorded Havasu floods occurred during late summer, fall, or mid-winter. Phenological studies indicate that velvet ash in southeastern Arizona buds, flowers, and develops leaves in early April during the fore-summer drought (Brock, 1994). Buds, leaves, and sprouts were observed on ash in Havasu Canyon on April 1, 1991. Cores collected in June 1991 possessed well-developed 1991 earlywood. Trees defoliated by the 1990 flood failed to regrow leaves, although most sprouted vigorously in early April 1991.

There are two important sources of error in the dendrochronological measurements. First, the simple ring counts reported here provide only approximate tree ages unless crossdating is successful. Unrecognized false or missing rings could lead to substantial error. There is no direct evidence for false or missing rings, however; the relative uniformity of ring width suggests few or no missing rings. Second, the pith from the outside of the tree was not recovered in some samples, and germination ages could be too young for these trees. Because samples were collected close to the base of trees, this error is probably three years or less.

Despite uniform streamflow and an moderate climate, ash trees in Havasu Canyon grow at very different rates (fig. 49). This variation makes it difficult to use tree diameter as an indicator of tree age. Even when measurements from a small area are used, the correlation of tree diameter and age is low; for example, the Beaver and Lower Mooney sites have regression coefficient (R^2) values of 0.2 and 0.4, respectively. Nevertheless, from the diameter and tree age data, it is possible to crudely estimate the length of time required for ash to recover from a severe forest disturbance in which most trees are killed. In 10 years, Havasu ash grow to diameters of 50 to about 300 mm. Thus, a mature-appearing riparian forest can establish on a formerly flood-scoured area in about 10 years.

The oldest velvet ash sampled in Havasu Canyon germinated in about 1900. These trees had narrow rings and modest diameters less than half those of the thickest trees. Rotten wood in the interior of oldest trees prohibited determination of exact ages. The older ash trees tend to be set back from the streambank as much as 100 m along junctures of tributaries with Havasu Creek. At

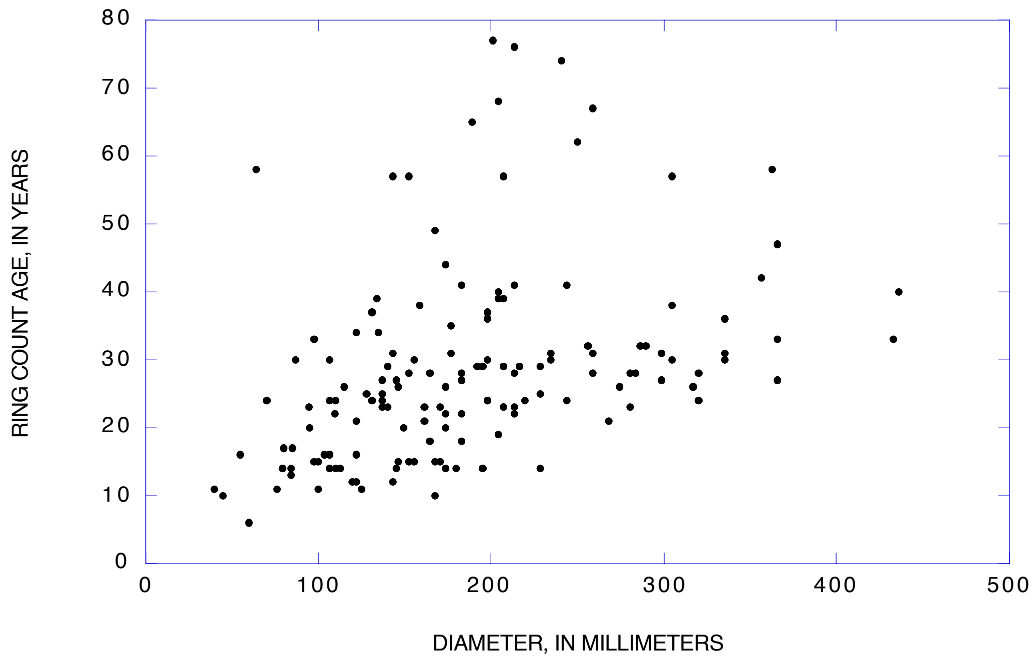


Figure 49. The relation between diameter at breast height and tree age of Havasu Creek ash trees.

these protected sites, they are not subjected to high stream energy during floods and receive moisture from ground water rather than directly from surface flow of Havasu Creek.

Histograms of tree ages (fig. 50) from the driftwood and the increment-core samples show multiple peaks and troughs superimposed upon a general pattern of increasing frequency of tree age toward the time of sampling in 1990 or 1991. The lack of trees dating from after 1980 is an artifact of sampling methods used. Most sampled trees began growth in the 1960s and 1970s, and only a very few date before 1940.

The peaks and troughs of the tree-age histograms invite correlation with historical floods. However, data from individual increment core sites (fig. 50) demonstrate that the Havasu riparian forest has a patchwork character that cannot be ascribed solely to flood effects. For example, historical photography suggests that the Havasupai campground reach experienced little vegetation change from 1940 to 1990 (figs. 31 and 32). On this basis, relatively old trees were expected at this locality; instead, increment cores from 20 trees show that this forest dates largely from the late 1960s to early 1970s (fig. 50c) and no tree older than 42 years was identified in the Havasupai campground reach. A similar result was obtained from trees below Mooney Falls (fig. 50d), which has stable riparian vegetation and channel morphology for the past 110 years (figs. 35 and 36). Despite this, the ages of 17 trees sampled below Mooney Falls range from only 9 to 47 years. Note that the two sites, although less than 1 km apart, share only one peak of forest recruitment at around 1949-1950; during other times, the two reaches appear independent in terms of forest recruitment.

Near Beaver Falls, a detailed study of sprouts growing from a single inclined trunk was conducted (fig. 50e). The ages of surrounding trees were also determined. The increment cores reveal that the trunk germinated in 1929, sprouted in 1950 and again in 1962, then was scarred in 1974. None of these dates correspond to known floods.

These results make interpretation of the driftwood data problematic in terms of flood frequency or magnitude. However, the driftwood and increment core data share two major features: a peak of recruitment in the 1960s and early 1970s and a general lack of trees older than 50 years. Scars on the driftwood (fig. 50b) also reflect forest disturbances in the 1970s, as well as the early

1980s; however, the origin of the driftwood scars cannot be determined with certainty.

Summary And Discussion

The age structure of the ash forest in Havasu Canyon is more complicated than initially anticipated and cannot be interpreted simply as a result of large floods. For example, at the lower Mooney and Havasupai campground localities, flooding apparently does not control tree mortality. At these protected sites, processes operating at smaller spatial scales than large floods (for example., windfall, insect depredation) apparently also limit tree longevity. These processes create a patchwork of trees with different germination or sprouting ages. Such processes may operate on an incremental basis, in that historical records and photography failed to document widespread vegetation destruction at these sites.

Non-flood processes limiting the life expectancy of trees include human disturbances, localized flooding, fire, fungal attack, rockfalls, and high winds. Evidence for each of these agents of tree mortality was observed in Havasu Canyon. Localized flooding occurs when tributary canyons receive intense rainfall from thunderstorms, but the bulk of the drainage remains unaffected by the storm; such occurrences were witnessed by Billingsley in 1970 (G. Billingsley, USGS, oral commun., 1994). Charred tree trunks from a recent fire were observed near Havasupai campground in June 1991. Such a fire may have been started by campers or lightening. Because Havasu Canyon is fuel-poor and the riverine zone is kept moist by the steady discharge of the creek, large fires seem unlikely and have not been reported; however, fire may limit tree age locally.

All of the oldest trees cored in Havasu Canyon contained heart rot, an important limiting factor for tree age. This suggests that fungal attack limits the age of ash trees by reducing structural integrity of the trunk; trees with extensive heart rot may be more susceptible to wind damage (G. Billingsley, USGS, oral commun., 1994). High winds during intense monsoon thunderstorms sometimes topple trees in Havasu Canyon (G. Billingsley, USGS, oral commun., 1994; L. Stevens, Bureau of Reclamation, oral commun., 1995), but topographic constraints limit wind damage to a small percentage of the forest. Finally, rockfalls are ubiquitous along

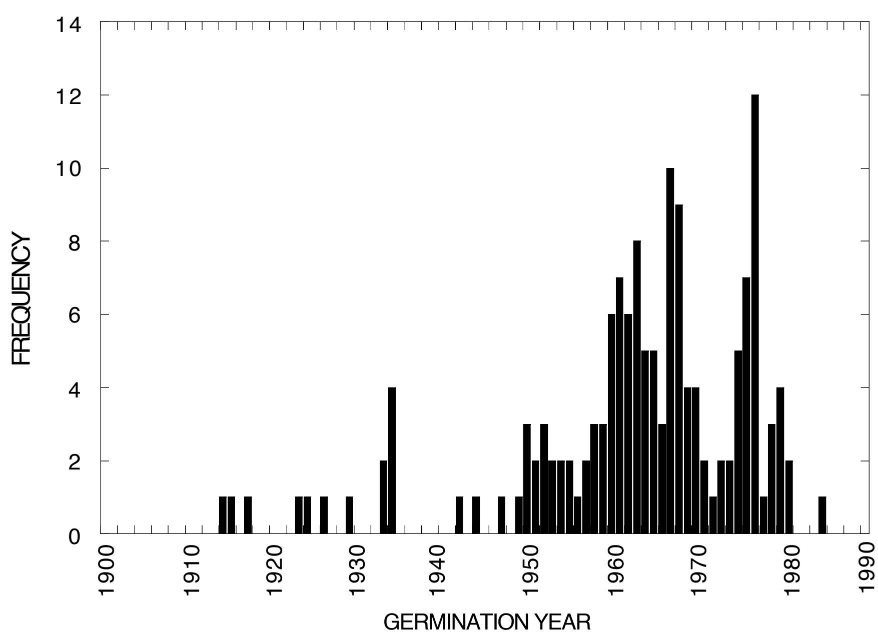
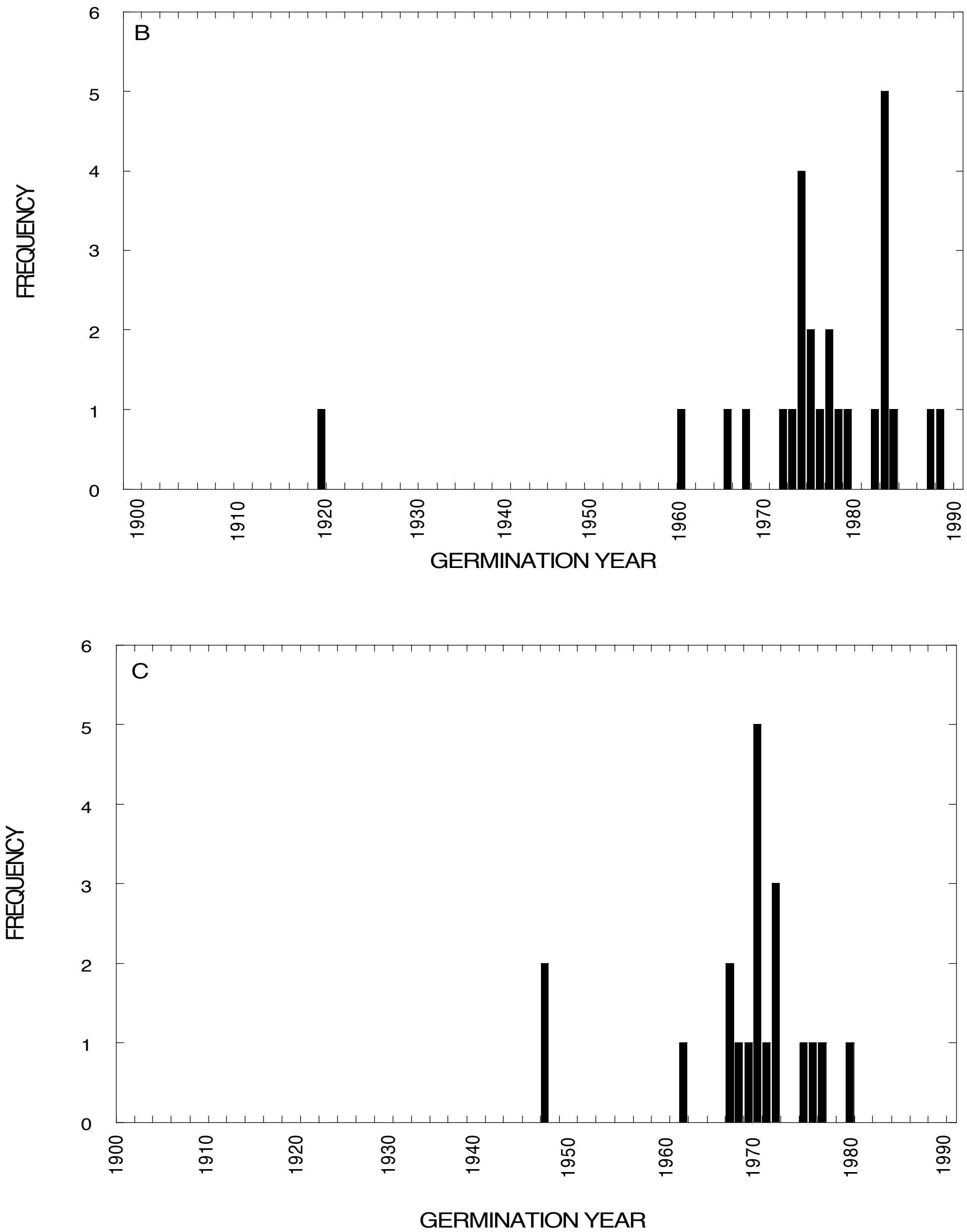
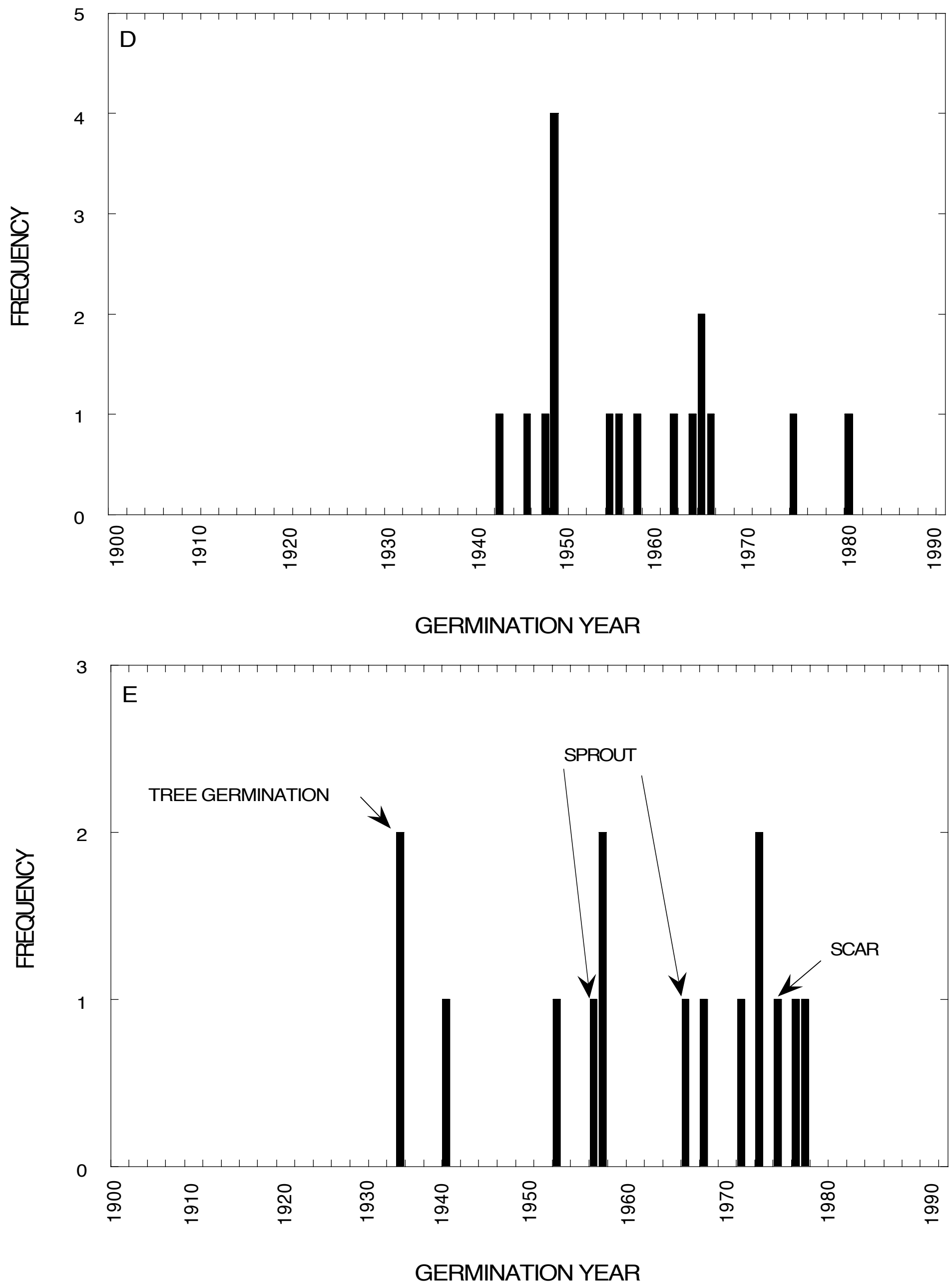


Figure 50. Histograms showing dendrochronology data obtained from ash trees destroyed by the 1990 flood or sampled in Havasu Canyon. For locations of dendrochronology sites, see figure 1c. A, Germination year of trees killed by the 1990 flood and transported into the Colorado River.



B, Years of scars found in trees killed by the 1990 flood and transported into the Colorado River. C, Germination year of ash trees cored at the Havasupai campground site.

Figure 50. Continued.



D, Germination year of ash trees cored at the Lower Mooney site. E, Germination year of ash trees cored at the Beaver Falls site. Several samples shown are adventitious sprouts or scars that reflect damage from floods or other reasons.

Figure 50. Continued.

the steep reaches of Havasu Creek, but the rockfalls are small and damage few trees.

Only insects and human beings rival large floods as agents of change in riparian forests. Historical and ethnographic records suggest that human activities were an important source of riparian forest disturbance in parts of Havasu Canyon. These activities include firewood collection, agriculture, cattle grazing, and the trampling of young tree sprouts by human foot traffic. The Havasupai have inhabited Havasu Canyon and surrounding areas for centuries (Iliff, 1954; Spier, 1979; Whiting and others, 1985). Havasupai agriculture, firewood collection, and the building of wood domestic structures probably disrupted the riparian habitat near Havasupai villages such as Supai prior to European contact. Because the Havasupai traditionally lived during winter months on the Plateau highlands above Havasu Canyon (Hirst, 1976; Dobyns and Euler, 1971), widespread firewood collection along the creek probably did not occur in winter. Avoidance of the area below Mooney Falls because of its use as a burial site may also have restricted Havasupai exploitation of this part of the drainage basin. These factors plus the low population of the Havasupai probably limited pre-European human influence on the riparian forest. The short life of riparian trees in Havasu Canyon prohibits testing of this hypothesis.

With the imposition of a reservation in 1882, the Havasupai were increasingly forced to live year-round at Supai. The need for firewood for cooking and heating, particularly in winter months, may have led to widespread riparian tree cutting in the vicinity of Supai. Other riparian changes at Supai are related to the development of European-style irrigated agriculture, including large plowed fields, planting of fruit orchards, and the digging of irrigation ditches. Cattle grazing may also have played a locally important role, particularly south of Supai in the Havasu springs region.

Evidence suggests that tourism and temporary non-Indian settlement have caused important recruitment changes in parts of the Havasu riparian ash forest. Heavy tourist use of the areas between Beaver Falls and the confluence of Havasu Creek and the Colorado River, and at the Havasupai campground, resulted in trampling of riparian vegetation. The trampling limits colonization of bare areas by willows, cottonwood, or ash. According to accounts by Billingsley (USGS, oral commun., 1994), the reach from Mooney Falls to the Colorado River confluence was temporarily inhabited by hundreds of people during the late 1960s and early 1970s. These transient people lived in tents and other temporary structures in Havasu Canyon downstream from Mooney Falls and harvested large amounts of firewood from riparian trees, leaving some areas of the canyon virtually deforested. Billingsley (USGS, oral commun., 1994) reported rapid colonization of the affected areas by riparian species following removal of the temporary settlers by the National Park Service in the mid-1970s. Although additional dendrochronological work is needed to define the full extent of humans on the Havasu riparian forest, it was tentatively concluded that the peak in ash recruitment in the late 1960s and early 1970s is related to the effects of the transient inhabitants of Havasu Canyon.

The greatest effect by floods on the age structure of riparian trees may have been the general lack of establishment before 1940. Repeated flooding during the early part of the 20th century may have destroyed much of the riparian forest, leaving only scattered trees in protected reaches. This suggestion is strongly supported by photographs taken immediately after the 1910 flood. Many of the trees then either succumbed to other agents of mortality, or are still present and were unaffected by later floods. The tree-ring data suggest that even when in flood-protected settings, most Havasu Canyon ash may have limited lifespans of up to 50 years and cannot be used to reconstruct a detailed record of floods. Ash trees grow at greatly different rates in Havasu Canyon despite a steady supply of water and a mild climate, and the riparian forest is a mosaic of trees of varying ages. In about 10 years, ash can recolonize a flood-scoured area and form a forest with an age structure similar to that of protected reaches.

HYDROCLIMATOLOGY OF FLOODS IN THE HAVASU CREEK DRAINAGE BASIN

Because of its large area and high topographic relief, the Havasu Creek drainage basin is affected by a variety of storm types that cause floods, including thunderstorms in summer and frontal system storms in winter. Storms that cause floods can be either local or regional in scale, and rainfall on an existing snowpack can greatly increase runoff. The intensity of these storms is influenced by orographic effects, travel paths inland from the Pacific Ocean, and seasonal to decadal scale variability in atmospheric circulation.

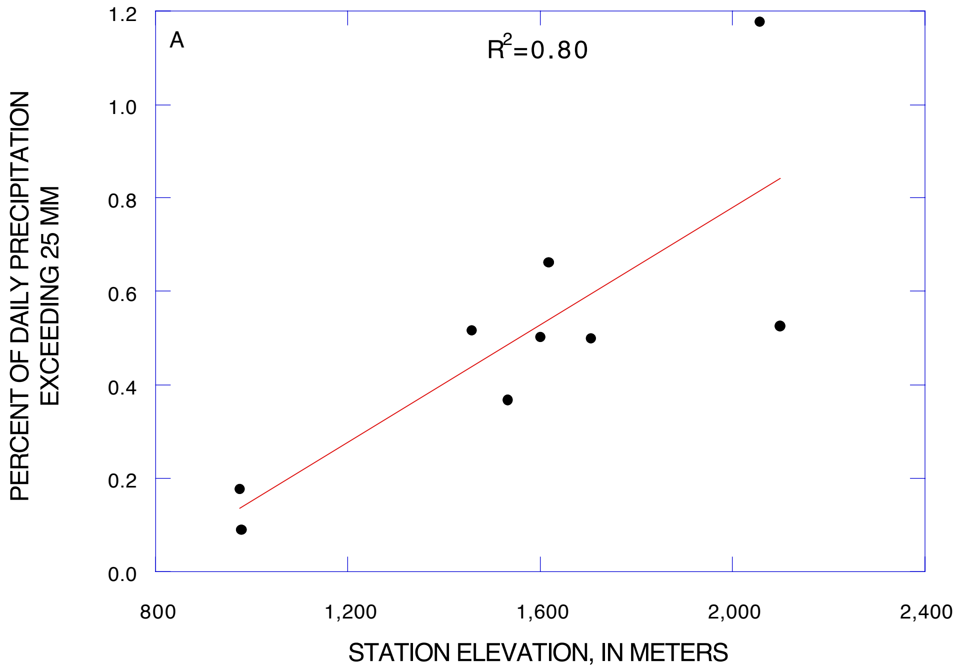
The moisture in storms that cause floods in the Havasu Creek drainage basin comes mostly from the eastern Pacific Ocean and Gulf of California, but the Gulf of Mexico is an important source during summer (Carlton and others, 1990). Moist, northerly airflow from the Gulf of Mexico and the eastern North Pacific Ocean creates Arizona's summer "monsoon," which can last from July through September (Andrade and Sellers, 1988). In most years, spring climate is characterized by prolonged periods of drought preceding the summer monsoon; as a result, floods do not occur between April and July in most of Arizona. This fact agrees well with the historical flood record for Havasu Creek.

Thomas and others (1994, p. 8) reported that flood regions in the southwestern United States have mixed populations of floods, creating "... an aggregation of floods that are caused by two or more distinct and generally independent hydrometeorologic conditions such as snow melt and rainfall." Floods in central Arizona are related to seasonally-varied storm types (Hirschboeck, 1985), and floods in other tributaries of the Colorado River in Grand Canyon have been related to summer monsoon thunderstorms, dissipating tropical cyclones, and winter frontal storms (Melis and others, 1994). Most floods documented in Grand Canyon tributaries from about 1940 through 1995 were generated by summer thunderstorms; however, the largest floods (including debris flows) during that period were caused by winter frontal storms and dissipating tropical cyclones (Cooley and others, 1977; Webb and others, 1989; Melis and others, 1994; Webb, 1996). Known Havasu Creek floods have only been caused by frontal storms three times; all other major historical floods were caused by thunderstorms (table 3).

Hereford and Webb (1992) and Graf and others (1991) suggest that fluvial erosion on the Colorado Plateau is driven mostly by warm-season precipitation occurring from June to November. The tendency for frequent summer floods in Grand Canyon tributaries agrees well with seasonal patterns of flooding recorded throughout the western United States. On the basis of 1,300 stream gage records in 10 states, most of the annual peak discharges between 29° and 37° N latitude have occurred from July through September (Thomas and others, 1994).

The documented 20th-century floods in Havasu Creek were related to general hydroclimatic conditions in the southwestern United States to determine if high frequency, low amplitude climatic fluctuations could explain the perceived pattern of historical floods. The percentage of days with >25 mm precipitation was tabulated for nine records (fig. 1a, tables 1 and 2) and related to latitude, longitude, elevation, and record length (fig. 51). Elevation, and to a lesser extent record length, correlate positively with frequency of daily precipitation >25 mm (figs. 51 a and b), whereas longitude and latitude show no correlation (figs. 51 c and d). On the basis of increases in flooding throughout Arizona over the last three decades, it was hypothesized that the annual frequency of intense daily precipitation (>25 mm) would trend positively during the latter part of the 20th century in records near Havasu Creek, and reflect a positive correlation with the occurrence of large floods in the 1990s.

Trends in daily precipitation >25 mm were evaluated for six climate stations in northwestern Arizona that are closest to Havasu Canyon -- Ashfork, Grand Canyon, Peach Springs, Seligman, Supai and Williams (fig. 1; tables 1 and 2) — during the periods of 1900-1929, 1930-1959, and 1960-1993, following the general approach of Webb and Betancourt (1992). The annual frequencies of daily precipitation >25 mm were



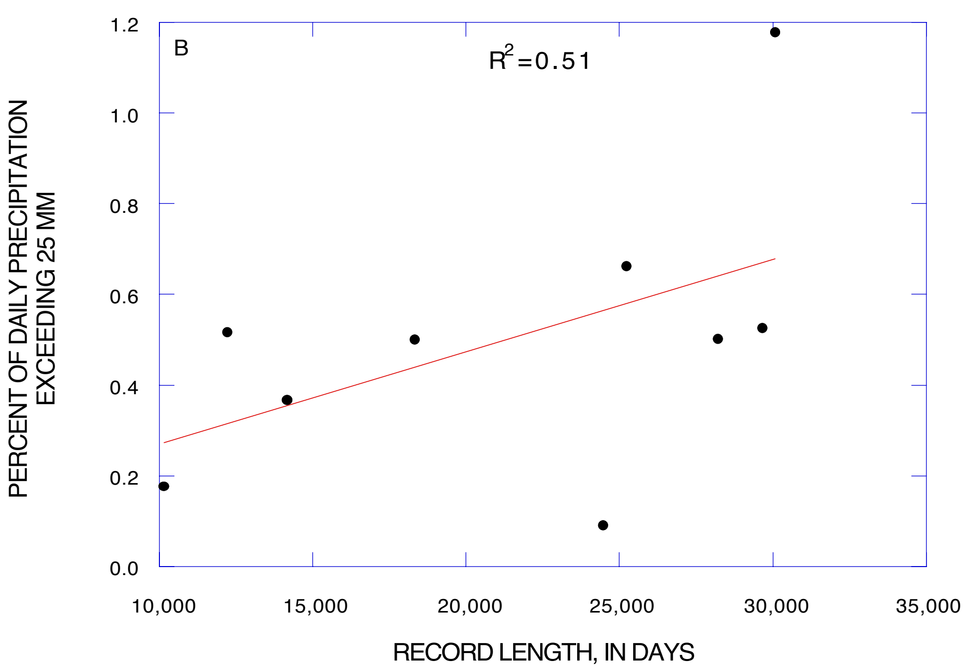
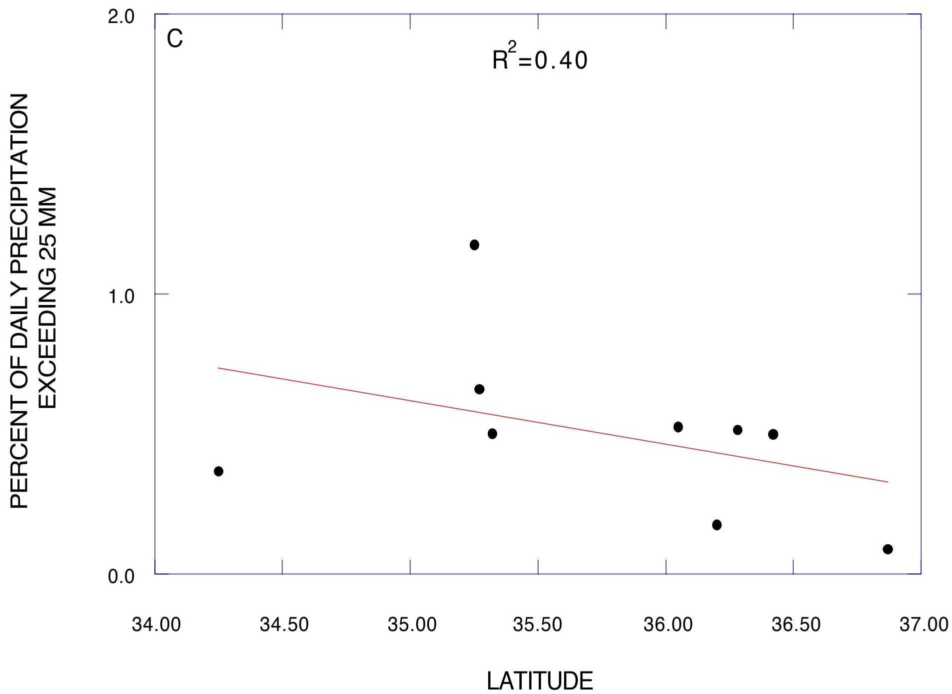
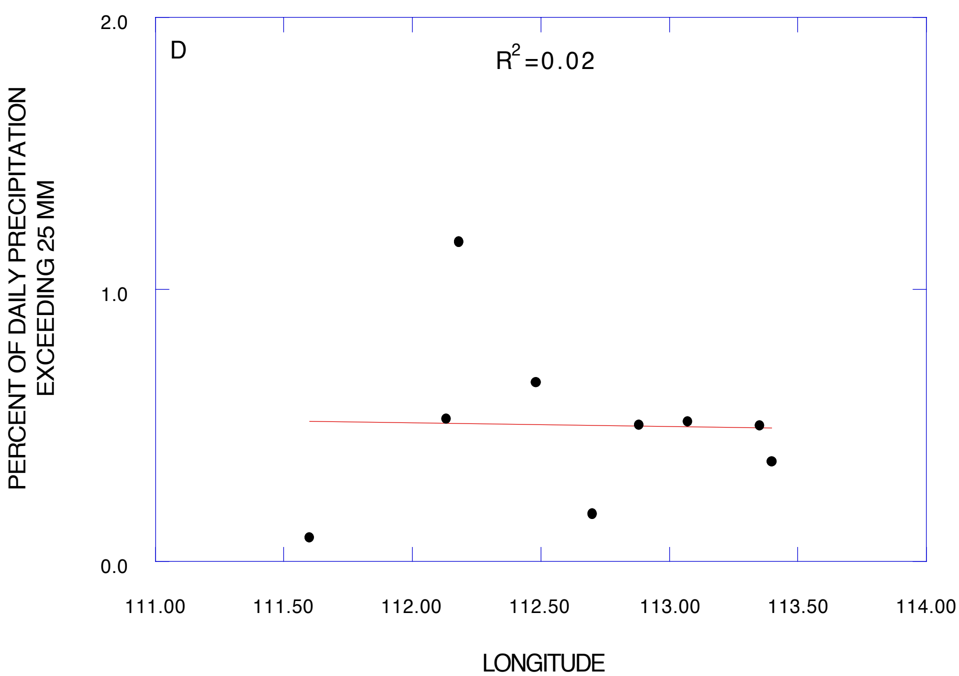


Figure 51. Relations between daily precipitation >25 mm and selected station characteristics for 9 records in the vicinity of Havasu Canyon. A, Elevation. B, Record length.

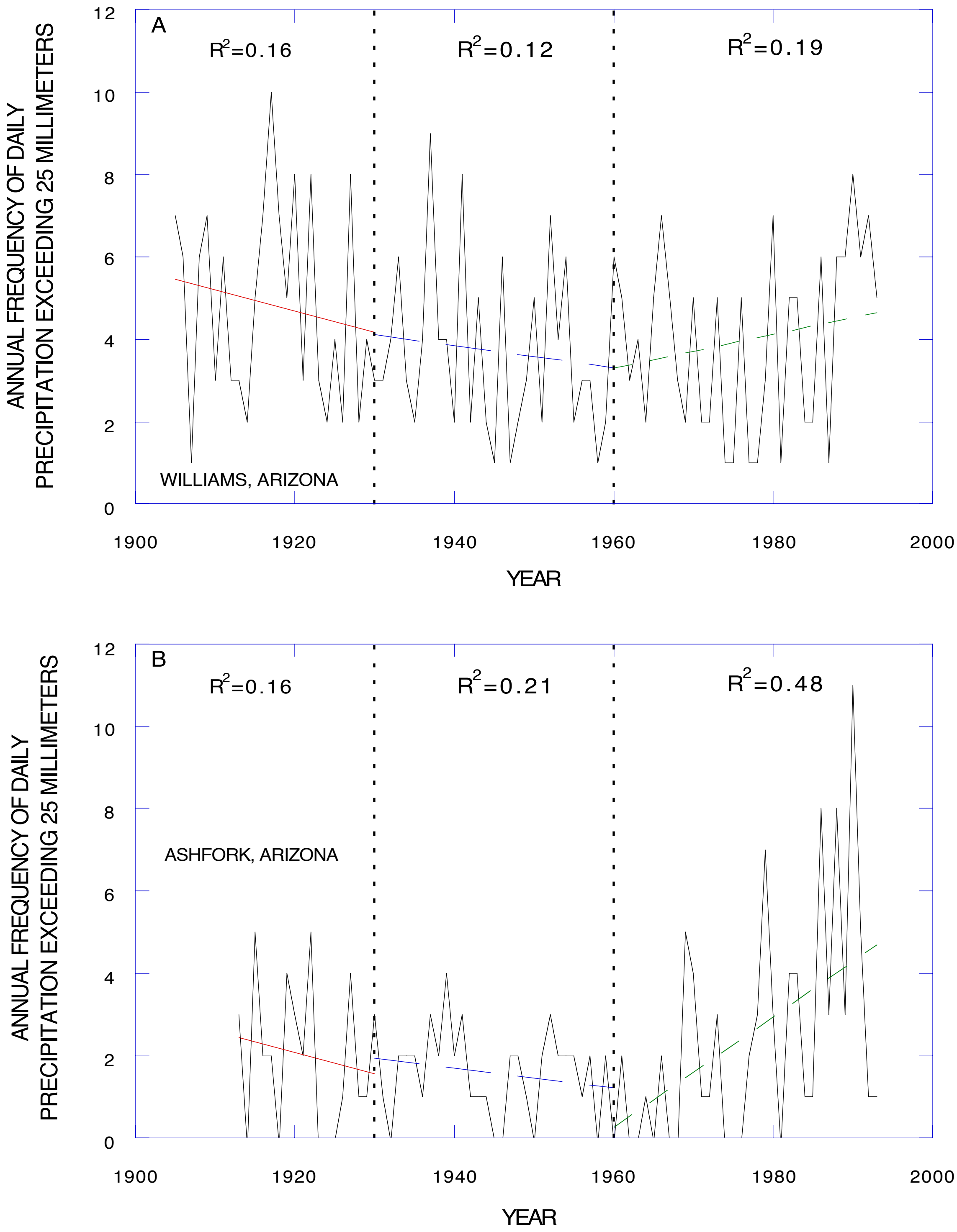




C, Latitude. D, Longitude

Figure 51. Continued.

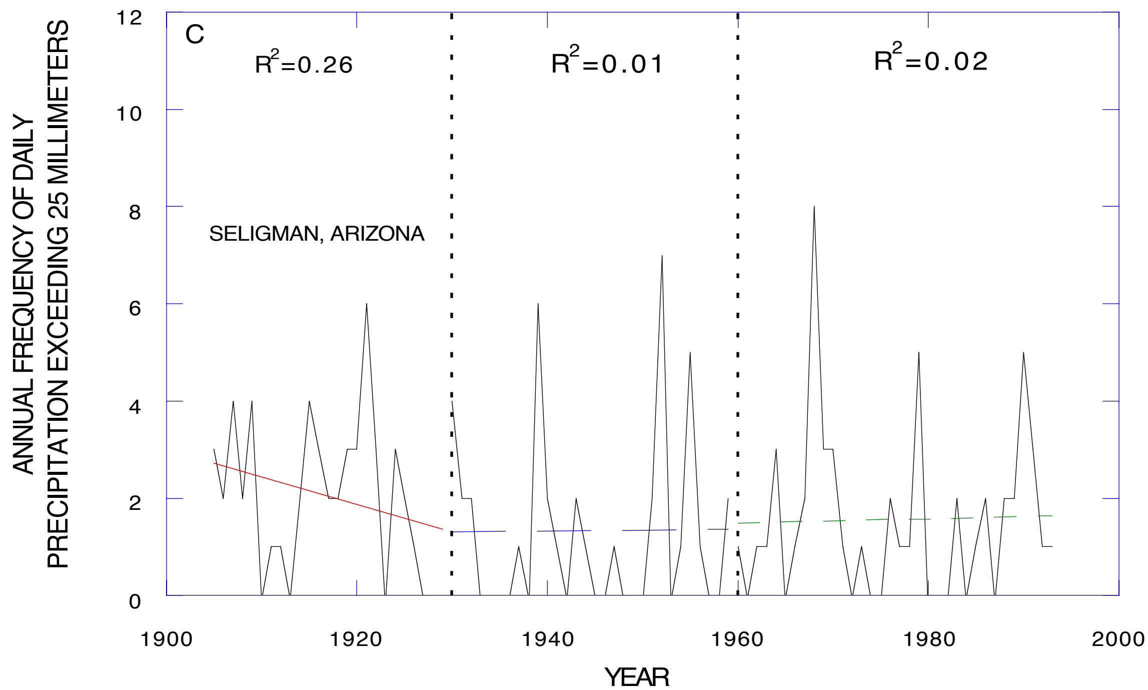
Figure 52. The number of days per year with precipitation >25 mm at selected stations in northern Arizona. Trend lines for the periods of early 1900s to 1930, 1930-1960, and post 1960 are determined from regression analysis. For the significance of the trends, see table 4. A, Williams. B, Ashfork.



A
R^2=0.16
R^2=0.12
R^2=0.19
WILLIAMS, ARIZONA
ANNUAL FREQUENCY OF DAILY PRECIPITATION EXCEEDING 25 MILLIMETERS
YEAR
B
R^2=0.16
R^2=0.21
R^2=0.48
ASHFORK, ARIZONA
ANNUAL FREQUENCY OF DAILY PRECIPITATION EXCEEDING 25 MILLIMETERS
YEAR

C, Seligman. D, Grand Canyon.

Figure 52. Continued.


C
R^2=0.26
R^2=0.01
R^2=0.02
SELIGMAN, ARIZONA
ANNUAL FREQUENCY OF DAILY PRECIPITATION EXCEEDING 25 MILLIMETERS
YEAR
0
2
4
6
8
10
12
1900
1920
1940
1960
1980
2000

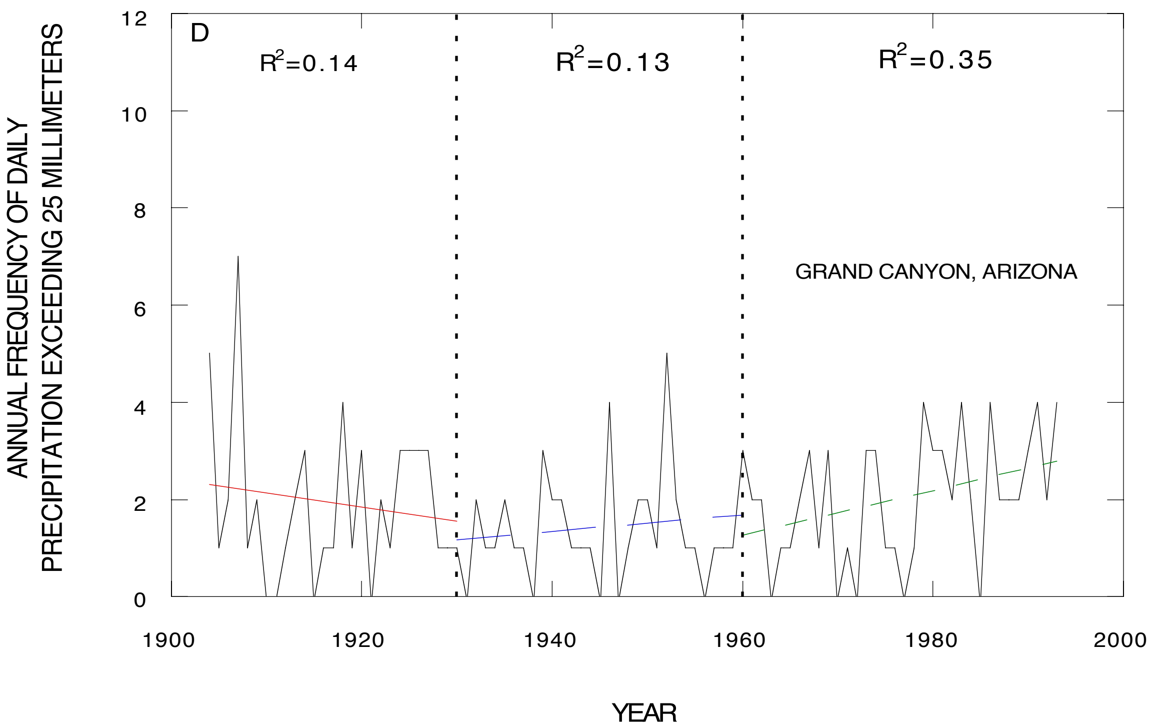

D
R^2=0.14
R^2=0.13
R^2=0.35
GRAND CANYON, ARIZONA
ANNUAL FREQUENCY OF DAILY PRECIPITATION EXCEEDING 25 MILLIMETERS
YEAR
0
2
4
6
8
10
12
1900
1920
1940
1960
1980
2000

Table 4. Results of Kendall Tau-b (nonparametric) statistics on trends in the annual frequency of daily precipitation >25 mm in records near Havasu Creek

[<0.05 probability was used for significance test]

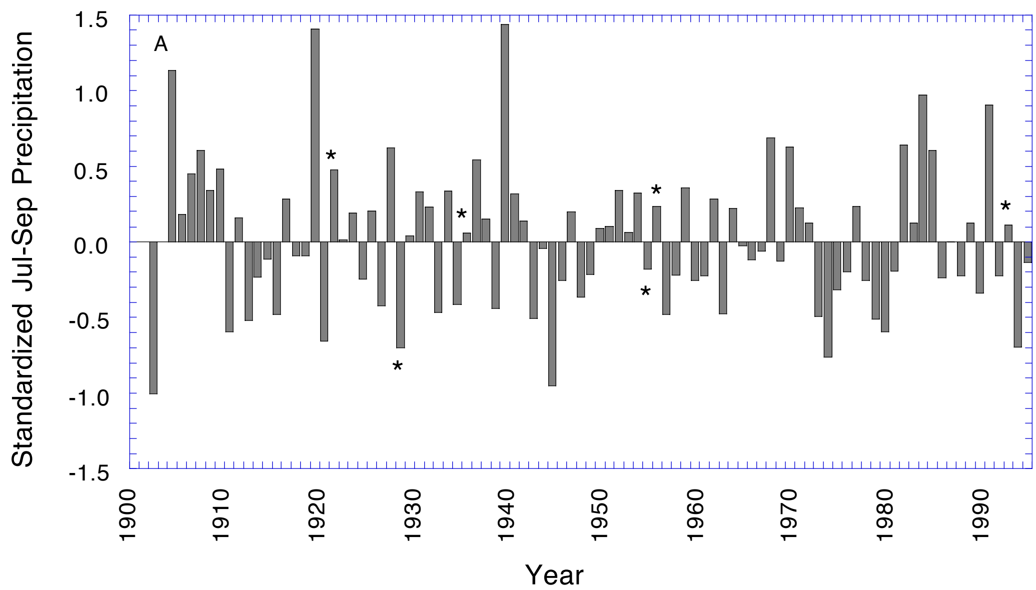
Precipitation Record	Period Analyzed	Years in Record	Trend	Kendall Tau-b (T)	Probability for Two-Sided Test
Ashfork	1900-1929	17	Slight Decrease	-0.151	0.368
Ashfork	1930-1959	30	None	-0.091	0.255
Ashfork	1960-1993	33	Increasing*	+0.369	0.003
Grand Canyon	1900-1929	26	None	+0.034	0.280
Grand Canyon	1930-1959	30	None	-0.008	0.255
Grand Canyon	1960-1993	33	Increasing*	+0.272	0.026
Peach Springs	1900-1929	n.d.	n.d.	n.d.	n.d.
Peach Springs	1949-1959	11	Decreasing	-0.414	0.491
Peach Springs	1960-1993	33	Decreasing	-0.159	0.194
Seligman	1900-1929	25	Decreasing	-0.216	0.287
Seligman	1930-1959	30	None	-0.038	0.255
Seligman	1960-1993	33	None	+0.058	0.638
Supai	1900-1929	n.d.	n.d.	n.d.	n.d.
Supai	1930-1959	n.d.	n.d.	n.d.	n.d.
Supai	1957-1987	21	Decreasing	-0.249	0.314
Williams	1900-1929	25	None	-0.084	0.287
Williams	1930-1959	30	Decreasing	-0.151	0.255
Williams	1960-1993	33	Increasing	+0.110	0.368

* indicates a statistically significant increasing trend in annual frequency of daily precipitation >25 mm; n.d., no data

tabulated for each of the periods (table 2), and trends in the data were tested for significance using a nonparametric statistical test (table 4).

What appeared to be trends in regression plots for the annual frequency of daily precipitation >25 mm from the first, middle, and latter thirds of the 20th century (fig. 52) were not uniformly significant. The precipitation increased significantly for 1960-1993 in two of the six records analyzed (Grand Canyon and Ashfork, fig. 52; table 4). Such a trend at Grand Canyon and Ashfork since 1960 likely explains, in part, the increased flood frequency in Havasu Creek that eventually resulted in the large floods of 1990, 1992, and 1993. The increasing trend toward intense daily precipitation suggests that climatic nonstationarity may be an important factor in understanding future flood frequency in the Havasu Creek drainage basin. Similar precipitation and flood-frequency trends were recently reported by Webb and Betancourt (1992) in Arizona. Karl and others (1995) found an increasing trend in daily precipitation >50 mm throughout many areas of the United States. In addition to the increasing trend, the data also suggested that precipitation between 1929 and 1960 was less intense (fig. 52). Although not a significant trend when tested using nonparametric statistics, that period of reduced, intense precipitation corresponded well with flood accounts and photographic evidence in Havasu Canyon between about 1940 and 1970.

On the basis of precipitation records at Grand Canyon and Ashfork for 1900-1930, the number of years with more than 7 days of precipitation >25 mm was high and may have been related to large historically-documented floods. Precipitation at Seligman from 1900 through 1930 shows a decreasing trend in precipitation that is not statistically significant. The annual frequency of precipitation >25 mm remained relatively lower from about 1930 to 1960 at all six stations examined near Havasu Creek, but significantly increased again in two of six records after 1959.



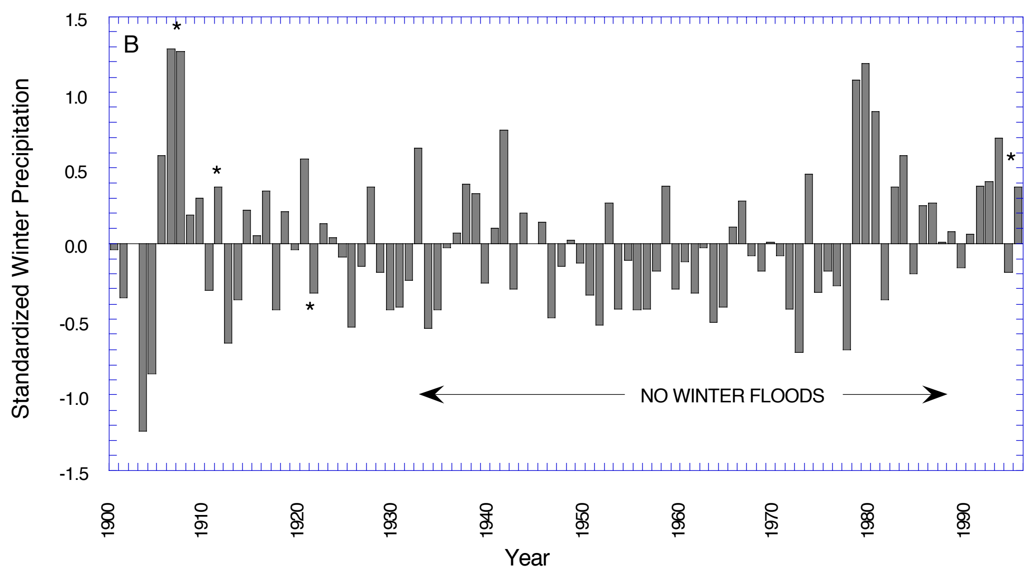


Figure 53. Standardized time series for seasonal precipitation at nine northern Arizona stations from about 1900 through 1995. * indicates the year of a flood. A, July through September rainfall. B, November through March precipitation.

Two time series were generated of standardized seasonal precipitation for all nine northern Arizona stations shown in Tables 1 and 2. The summer and winter seasons were defined as July through September, and November through March, respectively in these analyses. Most documented floods (eleven of fourteen) in Havasu Creek occurred from July through September and were caused by thunderstorms. Nearby climatic stations only occasionally recorded unusually high precipitation on the dates of Havasu Creek floods (table 3 and appendix 4). More often than not, storms associated with Havasu Creek floods had estimated recurrence intervals of five years or less, on the basis of data from stations within 120 kilometers of Supai (table 3). Only storms associated with the winter, 1993 flood were estimated to be extremely unusual (table 3).

The seasonal time series (fig. 53) provided a clearer perspective on relations between climate and flooding in Havasu Creek in the 20th-century. The interannual variability of summer precipitation has generally decreased in northern Arizona throughout the 20th century, and summer precipitation was below normal in most years after 1960 (fig. 53a). Highly variable and above-normal indices occurred in summers between 1908 and 1943. Several summer floods occurred in Havasu Canyon during this period, but correlation between the timing of floods and above-normal rainfall was poor (fig. 53a). Standardized winter precipitation clearly showed patterns of above-normal precipitation during the first and last thirds of the 20th century (fig. 53b). In addition, below-normal winter rainfall occurred during the middle portion of the 20th century. The overall pattern of the winter standardized precipitation series generally agrees with the trends of annual frequency for daily precipitation >25 mm.

The trend of above normal winter precipitation after about 1978 corresponds well with an increased frequency of large floods throughout Arizona over the last two decades (Webb and Betancourt, 1992; Ely and others, 1994), as well as the return of large floods in Havasu Creek in the 1990s. Persistence of this trend toward above-normal winter precipitation throughout northern Arizona might provide the best short-term forecasting tool for winter floods in Havasu Creek. Summer rainfall indices in northern Arizona have too much interannual variability to show trends that might foretell future flood patterns in Havasu Creek.

The Pacific Ocean temperature and atmospheric-pressure anomaly, commonly known as El Niño, (referred to jointly as ENSO (Southern Oscillation); see Diaz and Markgraf, 1992; Andrade and Sellers, 1988) is recognized as a reliable indicator of an increased probability of flooding throughout the western Americas. Relations between ENSO in the Pacific Ocean and streamflow in the southwestern United States suggest that streamflow is positively correlated with changing conditions of temperature and atmospheric pressure in the Pacific Ocean (Kahya and Dracup, 1993; Cayan and Webb, 1992). This correlation reflects the increased precipitation and delayed timing of winter storms from late fall to spring that is characteristic of El Niño years. Karl and others (1995) recently suggested that changes in the delivery patterns of regional and global precipitation patterns are likely related to changes in atmospheric temperature extremes and may be related to more frequent ENSO conditions recently observed between 1989 and 1995.

Changes in atmospheric circulation patterns from dominantly zonal to meridional flow over the western United States are commonly observed during El Niño conditions (Webb and Betancourt, 1992). However, meridional flow has recently occurred at a more frequent rate than during other periods of the 20th century and correlates with increased flooding in regions such as Arizona and California. Meridional circulation can increase the transport of warm, moist air from the eastern Pacific Ocean into areas such as Arizona and result in increased frequency and magnitude of floods. The recent persistence of ENSO, its identification as a flood-forcing mechanism, and the strong relation with 1990s floods in Havasu Creek warranted an examination of long-term ENSO records relative to historical Havasu Creek floods.

El Niño years were identified by the persistence of negative southern oscillation indices over five or more months in any two year period (Webb and Betancourt, 1992). Known Havasu Creek floods occurred in conjunction with ENSO events in seven out of fourteen years (table 5). Often, about a six- to ten month lag time can occur between the onset of El Niño conditions in the Pacific Ocean and occurrence of heightened streamflow in the western

Table 5. Relationship between El Niño/Southern Oscillation (ENSO) occurrence and historical floods in Havasu Creek

[ENSO, occurrence defined here by five or more consecutive months of negative southern oscillation indices during any 2-year period (1882-1995; Webb and Betancourt, 1992); Flood Magnitude, based on historical descriptions and photographs documented in this report]

Year of Flood	Summer	Winter	ENSO	Flood Magnitude
1899	[1]X		X	3
1904	[1]X		X	2
1905		[1]X	X	3
1910		X	[2]	5
1920		X	X	4
1921	X		[2]	2
1928	X			3
1935	X			3
1954	X		[2]	1
1955	X			2
1970(3)	X		[2]	0
1990	X		X	4
1992	X		[2]X	2
1993		X	[2]X	3

[1] season of flood was inferred from precipitation data; [2],the year of the flood followed an ENSO; [3],ten summer floods of approximately equal magnitude.

U.S. (Cayan and Webb, 1992; Webb and Betancourt, 1992). Of the fourteen floods identified in Havasu Creek over the last century, eleven occurred either in an El Niño year, or in a year immediately following an El Niño event, which is a seventy-eight percent correspondence (table 5).

Additional understanding of relationships between Havasu Creek flooding and ENSO will require additional hydroclimatic research and continued collection of stream-gage data. However, results of the present correlation can provide one useful predictive tool for anticipating large floods in this drainage basin. Improvements in long-term forecasting of ENSO conditions based on changes in the Pacific Ocean, combined with a flood-warning system based on precipitation and soil moisture monitoring, may result in increased flood preparedness for residents and visitors to Havasu Canyon in the future.

Summary and Discussion

Trends in the frequency of annual daily precipitation >25 mm generally reflect the historical patterns of channel erosion and riparian plant disturbance in Havasu Canyon after 1960. Although some trends in precipitation were not statistically significant (*e.g.*, decreasing trends from 1900-1929, fig 52), floods in the southwestern United States decreased between about 1940 and 1960 (Webb and Betancourt, 1992). Increasing trends in the frequency of annual daily precipitation >25 mm from 1960 through 1993 were identified in some precipitation records near Havasu Canyon, and help to explain the conclusions derived from repeat photographs, particularly those that show renewed disturbance of riparian vegetation and erosion of waterfalls after 1989.

Winter precipitation at stations in the vicinity of Havasu Canyon closely followed patterns of historical flooding. Increased winter precipitation in northern Arizona after 1978 corresponds to the pattern of increased large floods throughout Arizona as well as with the floods in Havasu Canyon from 1990 through 1993. An earlier pattern of frequent, above-normal winter precipitation during the first one-third of the 20th century was followed by frequent negative indices during the middle third of the century. This pattern is in agreement with the lower magnitude and frequency of floods, and agrees with recruitment patterns of riparian ash trees in Havasu Canyon

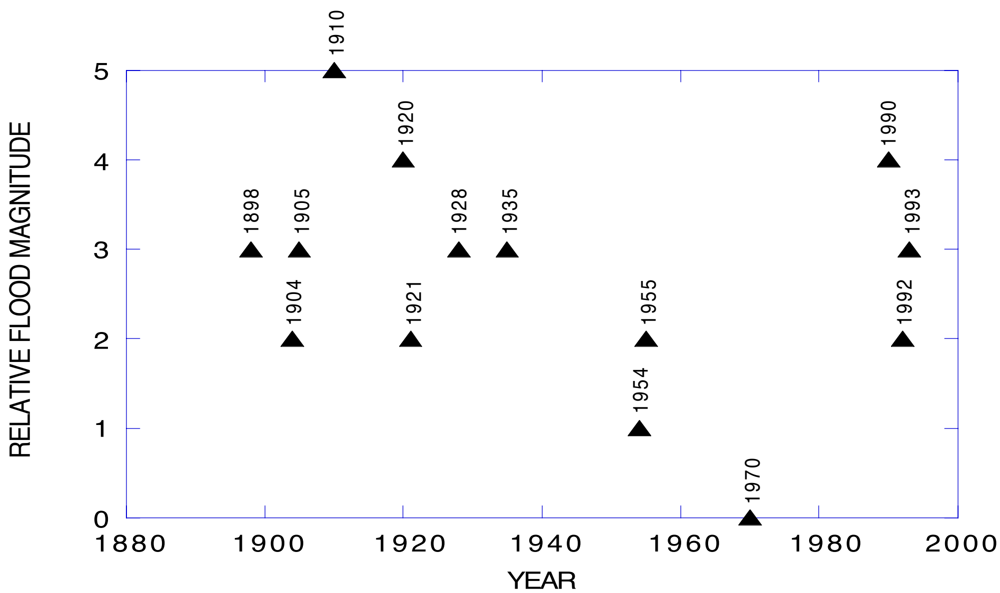


Figure 54. The relative magnitudes of Havasu Creek floods from 1899 through 1993 determined from historical flood accounts and repeat photography (see text for an explanation of the magnitude scale).

after about 1940. On the basis of the increasing precipitation trends in northern Arizona after 1960 at some stations near Havasu Creek, and the recent persistence of El Niño conditions in the eastern Pacific Ocean, floods of a similar magnitude to those in Havasu Creek from 1990 through 1993 might continue, and therefore should be anticipated.

The 20th-century pattern of flooding in Havasu Creek generally parallels the variability of flooding reported in other southwestern United States drainage basins, such as the Santa Cruz River of southern Arizona (Webb and Betancourt, 1992), the Paria River of north-central Arizona (Graf and others, 1991), the Virgin River of southern Utah (Hereford and other, 1995), Kanab Creek in southwestern Utah and northwestern Arizona (Webb and others, 1991), and the Little Colorado River (Hereford, 1984). Recent studies that reconstructed flood histories in other large drainage basins in the southwestern United States reported instrumental and proxy data indicating higher frequency and magnitude of flooding from the late 19th to the early to mid 20th century. Apparently, that period was followed by a marked reduction in flood magnitude and frequency after about 1940. The decline in flooding was typically related to decadal-scale climate variability related to eastern Pacific-Ocean sea-surface temperatures changes and circulation.

Webb and Betancourt (1992) concluded that variations in flood frequency of the Santa Cruz River, and the return of climatic conditions favoring large floods after about 1960 have implications for other southwest drainages, such as Havasu Creek. Similar studies have not been as thorough in northern Arizona, owing to the lack of long-term gaging data. However, similar relations between climate and floods could be reflected by the return of large recent floods in Havasu Creek and other nearby drainage basins since 1990, and the one-to-one relationship between recent Havasu Creek floods and unusually-persistent El Niño conditions (1990-1995). As more floods occur in Havasu Canyon, other hydroclimatic relations, such as those documented for the Santa Cruz River, may become clearer. Until then, linkages between decadal-scale variability of atmospheric circulation patterns in the northern hemisphere, such as ENSO, and flood frequency characteristics of large, ungaged drainage basins should be further

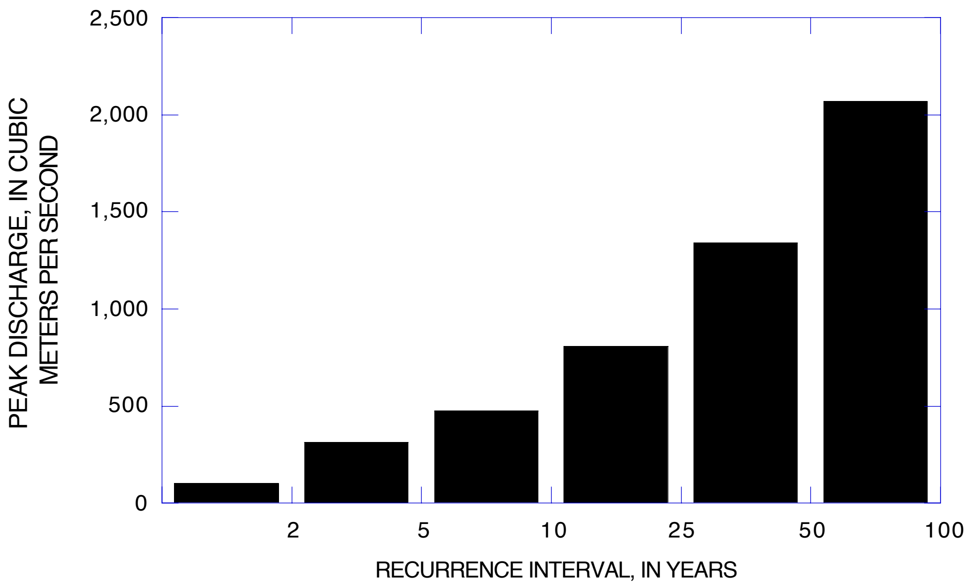


Figure 55. Estimates of peak discharge at 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals for Havasu Creek. Discharges were calculated from regional-regression relations for northeastern Arizona (Thomas and others,1994).

researched. If such linkages are real, then future variability in global-scale atmospheric circulation patterns will have large implications on assumptions of climatic stationarity, flood forecasting and flood-hazard preparedness in areas such as northern Arizona.

DISCUSSION AND CONCLUSIONS

Historical flooding in Havasu Canyon damaged the village of Supai, eroded travertine-controlled pools and waterfalls, formed an arroyo because of headward erosion, and uprooted and damaged riparian vegetation. Erosion from flooding was most severe from 1899 through about 1940, particularly during the January 1910 flood. Flooding has not occurred consistently in the 20th century; between about 1940 and 1990, Havasu Creek experienced few floods and little change was observed in the canyon's riparian features. Large floods of 1990 through 1993 caused erosion in Havasu Canyon, but the damaging effects of recent floods were apparently less than those caused by floods of 1899 to 1935, on the basis a variety of data.

Changes to waterfalls and plunge pools in Havasu Canyon were documented using repeat photography and historical accounts. The largest changes were in Fiftyfoot and Beaver Falls; Mooney Falls has changed little in the last 110 years. The most significant historical channel change in Havasu Canyon occurred in January 1910, when the lip of Havasu Falls was incised about 9 m. The abrupt change in base level created headward erosion from Havasu Falls upstream toward the village of Supai; the resulting arroyo attained a depth of about 9 m near the former position of Fiftyfoot Falls by 1993. Headward erosion of the arroyo apparently occurred mostly during the 1910 flood, but continued at a slower rate until about 1940, when erosion subsided and riparian vegetation became re-established. Future floods likely will result in continued headward erosion in Havasu Creek, possibly as far upstream as Supai.

Over the last century, Havasu Creek floods have occurred most frequently in summer and were caused by thunderstorms, although the largest and most destructive floods occurred following frontal storms in winter. Reports indicate that the discharges of the 1910 and 1993 winter floods were increased significantly by failures of earthen dams in the high-elevation headwaters of the drainage basin. The earthen dams will continue to pose a flood hazard to Supai and Havasu Canyon if they are not stabilized to withstand flood inflows, or capable of conveying bypass flows safely.

The flood of September 1990 damaged Supai, channelized flow through many travertine pools, and destroyed or damaged riparian vegetation in narrow reaches of Havasu Canyon downstream from Mooney Falls. The floods of July 1992 and February 1993 also caused erosion of the arroyo upstream of Havasu Falls, deposited gravel in Havasu Canyon, eroded travertine dams forming the plunge pool below Havasu Falls, and deposited a new debris fan at the confluence of Havasu Creek and the Colorado River. The coarse sediment deposited on the debris fan was likely derived from sediment stored on talus slopes throughout the canyon and in pools. In general, floods from 1990 through 1993 caused fewer changes in Havasu Canyon than did historical floods from 1899 through 1935. The 1990, 1992, and 1993 floods had peak discharges of 575, 95, and 391 m^3/s, respectively.

None of the evidence presented in this study is sufficient to estimate discharges of floods before 1990. As a result, the absolute magnitude of floods in Havasu Canyon before 1990 cannot be quantified accurately and a standard flood-frequency analysis cannot be made. Alternatively, a subjective classification of flood magnitude was devised on the basis of historical accounts, repeat photography, and tree-ring data. This subjective classification provides a way of conceptualizing 19th- and 20th-century flooding in Havasu Canyon (fig. 54).

In this classification, a magnitude 5 flood severely erodes most travertine pools and waterfalls in Havasu Canyon and severely damages riparian vegetation in the lower reaches of the canyon. Such a flood would also severely damage Supai (*e.g.*, the 1910 flood). In contrast, a magnitude O flood has a peak discharge only slightly above base flow; such a flood would likely cause no significant change to the channel or riparian vegetation in Havasu Canyon (*e.g.*, the summer 1970 floods). Floods of magnitudes 1-4 range accordingly between the two extremes described and are assigned to historically-documented floods depending on the erosional evidence identified from replicate photographs. According to this classification, the 1910 flood is assigned a magnitude 5 because of significant erosion to most waterfalls, severe damage to the riparian vegetation throughout Havasu Canyon, and the complete destruction of Supai. Floods reported by Billingsley during the summer of 1970 are assigned a magnitude of 0 because those floods had minimal impact on Havasu Canyon. The 1990 flood is assigned a magnitude 4 rating because of moderate to severe impacts on travertine deposits, riparian vegetation, and damage to Supai. Other historical floods are assigned relative magnitudes in comparison with the index floods described above. Graphic portrayal of this classification shows that Havasu Creek floods were large and relatively frequent from 1899 to about 1940; later floods were relatively small and occurred less frequently (fig. 54).

The regional-regression relations for flood frequency developed by Thomas and others (1994) were used to calculate standard recurrence-interval floods for Havasu Creek (fig. 55). On the basis of these estimates, the floods of 1990 through 1993 had recurrence intervals of 10-25 years, 2-5 years, and 5-10 years, respectively. The estimated 100-year flood for Havasu Creek — 2,070 m^3/s — is within the envelope curve reported for the region (Thomas and others, 1994, p. 56), although it appears to be an outlier in comparison to the other maximum peak discharges. Because the drainage area of Havasu Creek is larger than those of all other gaged streams in the region defined by Thomas and others (1994), the discharges may be poor estimates.

Discharges of the 1990s floods were compared with the 100-year flood for Havasu Creek and a regional flood-envelope curve for the southwestern United States (see Enzel and others, 1993). Relative to the largest known floods per unit area recorded in the Colorado River drainage basin, the 1990s floods are relatively small (fig. 56). The estimated 100-year flood for Havasu Creek plots close to, but below, the upper limit of peak discharges collected from drainages in the size range of Havasu Canyon. From this relation the potential for a flood approximately 3 times larger than the 1990 flood in Havasu Canyon is a possibility; a flood in this size range may have occurred in 1910. The apparent high variability of flood frequency in Havasu Canyon and the potential for floods as large as those estimated using

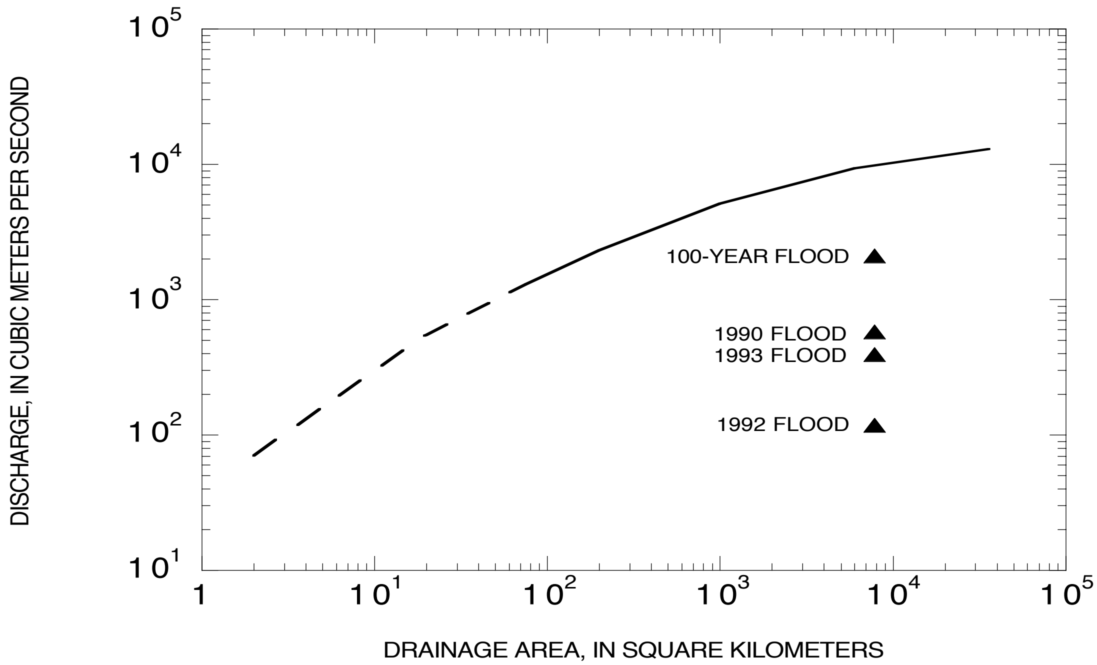


Figure 56. Envelope curve for floods in the Colorado River drainage basin (Enzel and others, 1992) showing the discharges of the 1990, 1992, and 1993 floods and the 100-year flood for Havasu Canyon (see fig. 55).

regression methods (Thomas and others, 1994) raise important questions of flood prediction and preparedness for the residents of Supai, and for the management of Havasu Canyon by the Havasupai and the NPS.

On the basis of evidence presented in this study, it is unlikely that a flood exceeding the estimated 25-year recurrence interval has occurred in Havasu Canyon since 1910. As a result of the apparent hiatus in destructive flooding from about 1940 to 1990, near-optimal conditions for growth in the riparian plant community of Havasu Canyon and for accumulation of travertine deposits were maintained for 40-50 years. The dense riparian vegetation and travertine pools that characterized Havasu Canyon from 1950 to 1990 may have reflected unusually stable environmental conditions in the lower reaches of the drainage basin during the middle part of the 20th century. Previous similar conditions likely were achieved for long periods on the basis of remnants of large travertine dams of unknown age observed throughout lower canyon reaches. Erosion of travertine deposits and riparian vegetation caused by early 1990s floods was relatively minor when compared with damage caused during the 1910 flood.

The riparian plant community rapidly recovered from the 1990 flood, but further damage was sustained during the floods of summer 1992 and winter 1993. Tree-ring data suggest that the riparian forest in Havasu Canyon may be regenerated in as few as 10 years. Therefore, a return to pre-1990 vegetation and stable travertine deposition may occur rapidly if large floods do not repeatedly occur in the near future. If large floods continue to occur, then the appearance of Havasu Canyon may resemble earlier conditions seen in historical photographs taken from 1910 through 1937 with scattered riparian trees and eroded channel conditions.

The pattern of historical floods in Havasu Creek generally paralleled the trend in annual frequency of precipitation >25 mm during the 20th century. Precipitation >25 mm increased significantly after 1960 at two of six climatic stations in the vicinity of Havasu Canyon. The increasing trend in precipitation generally supports similar findings in larger-scale studies of precipitation variability in the United States (Karl and others, 1995) and on the Colorado Plateau (Hereford and Webb, 1992). Most importantly, there is a strong relationship between 19th- and

20th-century flooding in Havasu Creek and ENSO conditions in the eastern Pacific Ocean.

Increasing trends in some nearby precipitation records since 1960, and the persistent occurrence of El Niño conditions, suggest that the probability for large floods in Havasu Creek will remain relatively high in the near future, as long as such conditions continue. Recent evidence of climatic nonstationarity in the southwestern United States, possibly related to shifts in atmospheric circulation and Pacific Ocean anomalies, makes the likelihood of accurately estimating flood frequency by conventional methods in drainages like Havasu Creek tenuous, if not impossible.

Continued uncertainty of future flooding potential in Havasu Canyon adds considerable complexity to management decisions related to an array of natural resources contained in this large Colorado River tributary. For example, resource managers have recently discussed introducing endangered native fishes of the Colorado River, such as humpback chub (*Gila cypha*), into Havasu Creek as a means of providing these unique fish with additional reproductive and rearing habitat. Such plans, as well as others related to human habitation and visitation, need to be carefully considered in light of the high potential for large, damaging floods in Havasu Creek; natural disturbances that occur infrequently and usually without warning.

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Appendix 1. Daily use in lower Havasu Canyon by river rafters from 1989 through 1990

[Data derived from "Attraction Site" monitoring program conducted by Grand Canyon National Park. Monitoring was designed to assess contact levels and density at popular attraction sites visited most often by river-runners. Surveys were conducted for periods of up to seven days during the summer months. Visitor destinations are shown in figure 1c. Mooney Falls, approximately 7 km upstream from the Colorado River, is usually the furthest destination of most hikers from river trips. Visit duration is correlated with hiking distance; for instance the Mooney Falls hike round trip requires a minimum of 4 to 5 hours from the river. "Big Kid's Pool," also formerly known as "Ruby pools," is the first pool where visitors from river trips stop to swim]

Date	Number of People	Havasu Creek Destination
1989		
04/20/89	10	Mooney Falls
04/21/89	11	Big Kid's Pool
04/23/89	4	Unknown
05/18/89	127	Big Kid's Pool
05/18/89	26	Mooney Falls
05/18/89	14	Beaver Falls
05/19/89	41	Beaver Falls
05/19/89	28	Big Kid's Pool
05/19/89	14	[1]Research
05/20/89	2	Mooney Falls
05/20/89	52	Big Kid's Pool
05/20/89	12	Beaver Falls
05/21/89	30	Beaver Falls
05/21/89	45	Big Kid's Pool
05/22/89	35	Mooney Falls
05/22/89	16	Beaver Falls
05/22/89	53	Big Kid's Pool
07/22/89	54	Mooney Falls
07/22/89	50	Beaver Falls
07/22/89	58	Big Kid's Pool
07/23/89	16	Beaver Falls
07/23/89	105	Big Kid's Pool
07/24/89	41	Beaver Falls
07/24/89	81	Big Kid's Pool
07/25/89	31	Beaver Falls
07/25/89	16	Big Kid's Pool

Appendix 1. Daily use in lower Havasu Canyon by river rafters from 1989 through 1990—Continued

Date	Number of People	Havasu Creek Destination
07/26/89	3	Mooney Falls
07/26/89	62	Beaver Falls
07/26/89	89	Big Kid's Pool
07/27/89	17	Beaver Falls
07/27/89	178	Big Kid's Pool
07/28/89	13	Beaver Falls
07/28/89	150	Big Kid's Pool
1990		
05/20/90	18	Mooney Falls
05/20/90	4	Beaver Falls
05/20/90	7	Big Kid's Pool
05/20/90	14	[1]Research
05/21/90	26	Mooney Falls
05/21/90	17	Big Kid's Pool
05/22/90	42	Big Kid's Pool
05/22/90	22	Mooney Falls
05/22/90	28	Beaver Falls
05/23/90	16	Beaver Falls
05/23/90	120	Big Kid's Pool
05/24/90	186	Big Kid's Pool
05/25/90	111	Big Kid's Pool
05/26/90	22	Beaver Falls
05/26/90	40	Big Kid's Pool
06/14/90	126	Beaver Falls
06/14/90	157	Big Kid's Pool
06/15/90	88	Beaver Falls
06/15/90	73	Big Kid's Pool
06/16/90	49	Beaver Falls
06/16/90	46	Mooney Falls
06/16/90	98	Big Kid's Pool
06/17/90	25	Beaver Falls
06/17/90	105	Big Kid's Pool

Appendix 1. Daily use in lower Havasu Canyon by river rafters from 1989 through 1990—Continued

Date	Number of People	Havasu Creek Destination
06/18/90	96	Beaver Falls
06/18/90	89	Big Kid's Pool
06/19/90	32	Beaver Falls
06/19/90	77	Big Kid's Pool
06/20/90	33	Beaver Falls
06/20/90	51	Big Kid's Pool
09/14/90	72	Big Kid's Pool
09/15/90	8	Beaver Falls
09/15/90	12	Mooney Falls
09/15/90	30	Big Kid's Pool
09/16/90	83	Big Kids Pool
09/17/90	24	Beaver Falls
09/17/90	15	Mooney Falls
09/17/90	54	Big Kid's Pool
09/18/90	31	Big Kid's Pool
09/18/90	130	Mooney and (or) Beaver Falls
09/19/90	16	Beaver Falls
09/19/90	24	Mooney Falls
09/19/90	22	Big Kid's Pool
09/20/90	41	Beaver Falls
09/20/90	58	Mooney Falls
09/20/90	95	Big Kid's Pool

[1]Indicates the party was conducting research and their destination was not known.

Appendix 2. Historical photographs of Havasu Canyon used in this study

[(RL), photograph was taken from the left side of the Colorado River; (CL), photograph was taken from creek-left; (CR), photograph was taken from creek-right; (US), upstream view; (DS), downstream view; (AC), view across the channel of Havasu Creek; (OA), oblique aerial view; (DV), view shows desert vegetation; (RV), view shows riparian vegetation; (AF), view shows agricultural fields; (WF), view shows waterfall(s); (P), view shows pool(s); (DF), view shows debris fan(s); (R), view shows Havasu Rapid on the Colorado River; (A), view shows an arroyo; (n.d.), no data; (n.a.), not applicable; (n.m.), the photograph was analyzed but not matched; photographs are listed in downstream order as they occur along Havasu Creek]

Year	Date	Photographer	Original number	Stake number	Side	Direction	Subject
Upstream of Supai:							
1885	Jun	Wittick	16100	2169	CL	DS	RV
1885	Jun	Wittick	16250	2170	CL	DS	RV
ca. 1899	n.d.	Peabody	8983-14730	2171	CL	DS	RV, DV
ca. 1899	n.d.	Peabody	8993-14741	2172	CL	US	RV
1910	Jan	Barnes	n.d.	2168	CR	DS	RV
Near Supai:							
1885	Jun	Wittick	16245	2173	CR	DS	AF, RV, DV
ca. 1899	n.d.	Peabody	8994-14742	2174	CL	DS	RV, DV
ca. 1900	n.d.	Bass	39	2175	CR	US	RV, DV
1941	Jun	Muench	B-1871	2176	CR	US	RV, DV, AF
1988	Jun	Brownold	n.d.	2149	CR	US	RV, DV, AF
1991*	Jun	Brownold	n.a.	2149	CR	US	RV, DV, AF
50-Foot Falls:							
1885	Jun	Wittick	16108	2177	CR	US	WF, RV
1937	Jun	Muench	107	2178	CR	US	WF, RV
1946	n.d.	Madden	n.d.	2179	CR	US	WF, DV
1970	Jul	Billingsley	n.d.	2180	CR	AC	WF, RV
Navajo Falls:							
ca. 1899	n.d.	Peabody	8984-14731	2156	CL	AC	WF, RV, DV
1991*	Jun	Melis	n.a.	2156	CL	AC	WF, RV, DV
1910	Jan	Barnes	n.d.	2871	CL	AC	WF, RV, DV
1994*	Oct	Melis	n.a.	2871	CL	AC	WF, RV, DV
1941	n.d.	Muench	B-1867	2181	CL	AC	WF, RV, P
1970	Aug	Billingsley	n.d.	2182	CL	AC	WF, RV
Between Navajo and Havasu Falls:							
1990	n.d.	Crumbo	n.d.	2197	CR	DS	A, RV
1994	Oct	Melis	n.a.	2879	CR	DS	A, RV
Havasu Falls:							
1885	Jun	Wittick	16253	2878	CL	US	WF, RV, P
1994*	Oct	Melis	n.a.	2878	CL	US	WF, RV, P
1885	Jun	Wittick	16254	2184	CL	AC	WF, RV, P
1885	Jun	Wittick	15470	2183	CL	US	WF, RV, P
1885	Jun	Wittick	16102	2875	CL	US	WF, RV, P
1994*	Oct	Melis	n.a.	2875	CL	US	WF, RV, P
1885	Jun	Wittick	16252	2873	CL	US	WF, RV, DV
1994*	Oct	Melis	n.a.	2873	CL	US	WF, RV, DV

Appendix 2. Historical photographs of Havasu Canyon used in this study—Continued

Year	Date	Photographer	Original number	Stake number	Side	Direction	Subject
ca. 1899	n.d.	Peabody	8981-14728	2153	CL	US	WF, RV
1991*	n.d.	Melis	n.a.	2153	CL	US	WF, RV
ca. 1900	n.d.	Bass	32	2157	CL	US	WF, RV
1991*	Jun	Melis	n.a.	2157	CL	US	WF, RV
1903	n.d.	Marshall	n.d.	2151	CL	US	WF, RV
1991*	Jun	Melis	n.a.	2151	CL	US	WF, RV
1903	n.d.	Marshall	n.d.	2152	CL	AC	WF, RV
1991*	Jun	Melis	n.a.	2152	CL	AC	WF, RV
1905	n.d.	Darton	n.d.	2872	CL	AC	WF, RV, P, DV
1994*	Oct	Melis	n.a.	2872	CL	AC	WF, RV, P, DV
1907	n.d.	Kolb	568-3469	2876	CL	US	WF, RV, P
1994*	Oct	Melis	n.a.	2876	CL	US	WF, RV, P
1907	n.d.	Kolb	568-8706	2877	CL	US	WF, RV, P
1994*	Oct	Melis	n.a.	2877	CL	US	WF, RV, P
1994	Oct	Melis	n.d.	2879	CR	DS	WF, RV
1910	Jan	Barnes	n.d.	2183	CL	AC	WF, RV
1937	n.d.	Muench	B-1848	2155	CL	AC	WF, RV, DV, P
1991*	Jun	Melis	n.a.	2155	CL	AC	WF, RV, DV, P
1947	n.d.	Breed	n.d.	2154	CL	AC	WF, RV, P
1991*	Jun	Melis	n.a.	2154	CL	AC	WF, RV, P
1968	Oct	Billingsley	n.d.	2874	CL	AC	WF, RV
1970*	Aug	Billingsley	n.d.	2874	CL	AC	WF, RV
1994*	Oct	Melis	n.a.	2874	CL	AC	WF, RV
1988	Jun	Brownold	n.d.	2144	CL	US	WF, RV, P
1991*	Jun	Brownold	n.a.	2144	CL	US	WF, RV, P
1988	Jun	Brownold	n.d.	2146	CL	US	WF, RV, P
1991*	Jun	Brownold	n.a.	2146	CL	US	WF, RV, P
Between Havasu and Mooney Falls:							
1903	n.d.	Marshall	n.d.	2163	CL	US	RV
1991*	Jun	Melis	n.a.	2163	CL	DS	RV
1903	n.d.	Marshall	n.d.	2880	CL	DS	RV
1994*	Oct	Melis	n.a.	2880	CL	DS	RV
1910	Jan	Barnes	n.d.	2883	CL	US	RV
1994*	Oct	Melis	n.a.	2883	CL	US	RV
1988	Jun	Brownold	n.d.	2148	CL	DS	P, RV, DV
1991*	Jun	Brownold	n.a.	2148	CL	DS	P, RV, DV
1988	Jun	Brownold	n.d.	2145	CL	US	RV
1991*	Jun	Brownold	n.a.	2145	CL	US	RV
Mooney Falls:							
1885	Jun	Wittick	15472	2886	CL	US	WF, RV, P
1994*	Oct	Melis	n.a.	2886	CL	US	WF, RV, P
1885	Jun	Wittick	16106	2882	CL	US	WF, RV, P
1994*	Oct	Melis	n.a.	2882	CL	US	WF, RV, P

Appendix 2. Historical photographs of Havasu Canyon used in this study—Continued

Year	Date	Photographer	Original number	Stake number	Side	Direction	Subject
1885	Jun	Wittick	16255	2186	CL	US	WF, RV, P
1885	Jun	Wittick	16105	2187	CL	US	WF, RV, P
ca. 1899	n.d.	Maude	n.d.	2161	CL	US	WF, RV, P
1991*	Jun	Melis	n.a.	2161	CL	US	WF, RV, P
ca. 1899	n.d.	James	n.d.	2165	CL	US	WF, RV, DV, P
1991*	Jun	Melis	n.a.	2165	CL	US	WF, RV, DV, P
1903	n.d.	Marshall	n.d.	2162	CL	US	WF, RV
1991*	Jun	Melis	n.a.	2162	CL	US	WF, RV
1907	n.d.	Kolb	n.d.	2159	CL	US	WF, RV, DV
1991*	Jun	Melis	n.a.	2159	CL	US	WF, RV, DV
1907	n.d.	Kolb	n.d.	2166	CL	US	WF, RV, DV, P
1994*	Oct	Melis	n.a.	2166	CL	US	WF, RV, DV, P
1907	n.d.	Kolb	568-8704	2881	CL	US	WF, RV, DV, P
1994*	Oct	Melis	n.a.	2881	CL	US	WF, RV, DV, P
1907	n.d.	Kolb	568-8702	2885	CL	US	WF, RV, DV, P
1994*	Oct	Melis	n.a.	2885	CL	US	WF, RV, DV, P
1939	n.d.	Muench	114	2160	CL	US	WF, RV
1991*	Jun	Melis	n.a.	2160	CL	US	WF, RV
1939	n.d.	Muench	115	2158	CL	US	WF, RV, P
1991*	Jun	Melis	n.a.	2158	CL	US	WF, RV, P
1947	n.d.	Breed	n.d.	2167	CL	US	WF, RV, DV, P
1991*	Jun	Melis	n.a.	2167	CL	US	WF, RV, DV, P
1968	Oct	Billingsley	n.d.	2188	CL	US	WF
1988	Jun	Brownold	n.d.	2147	CL	US	WF, RV, DV, P
1991*	Jun	Brownold	n.a.	2147	CL	US	WF, RV, DV, P
1991	Jun	Melis	n.a.	2164	CL	AC	WF, RV
<u>**Between Mooney and Beaver Falls:**</u>							
ca. 1899	n.d.	Peabody	8989-14737	2884	CL	DS	RV
1994*	Oct	Melis	n.a.	2884	CL	DS	RV
1903	n.d.	Marshall	n.d.	2189	CL	US	WF, RV
1988	Jun	Brownold	n.d.	2139	CL	US	RV, P
1991*	Jun	Brownold	n.a.	2139	CL	US	RV, P
1988	Jun	Brownold	n.d.	2140	CR	US	RV, P
1991*	Jun	Brownold	n.a.	2140	CR	US	RV, P
1988	Jun	Brownold	n.d.	2142	CL	US	RV
1991*	Jun	Brownold	n.a.	2142	CL	US	RV
1988	Jun	Brownold	n.d.	2143	CL	US	RV, DV
1991*	Jun	Brownold	n.a.	2143	CL	US	RV, DV
1988	Jun	Brownold	n.d.	2150	CL	US	RV
1991*	Jun	Brownold	n.a.	2150	CL	US	RV
<u>**Beaver Falls:**</u>							
1903	n.d.	Marshall	n.d.	2889	CR	US	WF, RV, P
1994*	Oct	Melis	n.a.	2889	CR	US	WF, RV, P

Appendix 2. Historical photographs of Havasu Canyon used in this study—Continued

Year	Date	Photographer	Original number	Stake number	Side	Direction	Subject
1903	n.d.	Marshall	n.d.	2190	CL	US	WF, RV, P
1907	n.d.	Kolb	568-6147	2191	CL	US	WF, RV, P
1907	n.d.	Kolb	568-6148	2192	CL	US	WF, RV, P
1937	n.d.	Muench	112	2888	CR	US	WF, RV, DV, P
1994*	Oct	Melis	n.a.	2888	CR	US	WF, RV, DV, P
1970	Sep	Billingsley	n.d.	2887	CR	US	WF, RV, P
1994*	Oct	Melis	n.a.	2887	CR	US	WF, RV, P
1988	Jun	Brownold	n.d.	2141	CL	US	WF, RV, P
1991*	Jun	Brownold	n.a.	2141	CL	US	WF, RV, P
Between Beaver Falls and the Colorado River:							
1923	Sep	Larue	575	2238	CL	US	RV, DV, P
1991*	Oct	Melis	n.a.	2238	CL	US	RV, DV, P
1923	Sep	Larue	574	2870	CL	US	RV, DV, P
1994*	Sep	Melis	n.a.	2870	CL	US	RV, DV, P
1937	n.d.	Muench	110	2193	CL	US	RV
1990	n.d.	Crumbo	n.d.	2198	OA	OA	RV
Havasu Canyon and Colorado River Confluence:							
1885	Jun	Wittick	16099	2869	RL	US	R, DV
1994*	Sep	Webb	n.a.	2869	RL	US	R, DV
1885	Jun	Wittick	15501	2832	RL	DS	R, DV
1994*	Mar	Grijalva	n.a.	2832	RL	DS	R, DV
1911	Jan	Kolb	568-5815	2655	RL	US	R, DF, DV
1993*	Mar	Tharnstrom	n.a.	2655	RL	US	R, DF, DV
1923	Sep	LaRue	571	2596	RL	US	R, DF, DV
1993*	Mar	Hymans	n.a.	2596	RL	US	R, DF, DV
1923	Sep	LaRue	572	2597	CL	DS	DV
1993*	Mar	Tharnstrom	n.a.	2597	CL	DS	DV
1923	Sep	Larue	569	2367	CL	US	DV
1991*	Oct	Melis	n.a.	2367	CL	US	DV
1947	n.d.	Marston	n.d.	2831	RL	US	R, DF, DV
1994*	Mar	Tharnstrom	n.a.	2831	RL	US	R, DF, DV

* indicates a match of the earliest photograph with the same stake number.

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Appendix 3. Dendrochronology data collected from ash (Fraxinus sp.) trees along Havasu Creek

PART 1. DATA ON DRIFTWOOD COLLECTED ALONG THE COLORADO RIVER

Sample number	[1]River mile	Condition of slab	[2]Diameter (mm)	Ring count	Year of inner ring (AD)
1	158 3	WHOLE	195.1	29	1962
2	158.5	WHOLE	213.4	23	1968
3	158.6	WHOLE	112.8	14	1977
4	158.9	WHOLE	131.1	37	1954
5	159.0	WHOLE	134.1	39	1952
6	160.9	WHOLE	432.8	33	1958
7	163.0	BROKEN	216.4	29	1962
8	163.0	HALF SLAB	182.9	22	1969
9	163.0	BROKEN	243.8	24	1967
10	164.5	SPLIT	167.6	10	1981
11	161.5	WHOLE	70.1	24	1967
12	161.5	WHOLE	106.7	16	1975
13	161.5	SPLIT	158.5	38	1953
13.5	164.5	WHOLE	182.9	41	1950
14	164.5	WHOLE	106.7	24	1967
15	164.5	WHOLE	176.8	31	1960
16	164.5	HALF SLAB	76.2	11	1980
17	164.5	WHOLE	155.4	15	1976
18	164.5	WHOLE	195.1	14	1977
19	164.5	WHOLE	192.0	29	1962
20	164.8	WHOLE	286.5	32	1959
21	166.0	BROKEN	137.2	7	1964
2'	166 0	VALUE	243.8	41	1950
23	166.0	VALUE	207.3	39	1952
24	166.0	WHOLE	204.2	39	1952
25	166.0	WHOLE	213.4	41	1950
26	168.0	WHOLE	170.7	23	1968
27	168.0	WHOLE	182.9	28	1963
28	168.0	WHOLE	228.6	29	1962
29	168.0	WHOLE	176.8	35	1956
30	168.0	WHOLE	137.2	23	1968
31	168.0	WHOLE	140.2	29	1962
32	168.0	SCAR	106.7	30	1961
33	168.0	WHOLE	103.6	16	1975
34	168.0	SCAR	109.7	22	1969
35	168.0	WHOLE	79.2	14	1977
36	168.0	ROTTED CORE	240.8	74	1917
37	168.0	WHOLE	213.4	76	1915
38	168.4	BROKEN	198.1	37	1954
39	168.6	WHOLE	189.0	65	1926

Appendix 3. Dendrochronology data collected from ash (Fraxinus sp.) trees along Havasu Creek—Continued
PART 1. DATA ON DRIFTWOOD COLLECTED ALONG THE COLORADO RIVER

Sample number	[1]River mile	Condition of slab	[2]Diameter (mm)	Ring count	Year of inner ring (AD)
40	171.6	WHOLE	289.6	32	1959
41	171.6	WHOLE	173.7	26	1965
42	171.6	WHOLE	259.1	28	1963
43	171.7	WHOLE	97.5	33	1958
44	171.7	WHOLE	143.3	31	1960
45	171.7	WHOLE	207.3	29	1962
46	171.7	WHOLE	280.4	28	1963
47	171.8	BROKEN	182.9	27	1964
48	171.8	WHOLE	121.9	21	1970
49	171.8	WHOLE	164.6	18	1973
50	171.8	WHOLE	79.2	14	1977
51	171.8	WHOLE	198.1	24	1967
52	172.9	WHOLE	137.2	24	1967
53	172.9	WHOLE	137.2	25	1966
54	174.3	WHOLE	234.7	30	1961
55	174.3	WHOLE	173.7	20	1971
56	174.3	PARTIAL	335.3	36	1955
57	174.3	PARTIAL	198.1	36	1955
58	174.3	WHOLE	173.7	14	1977
59	174.3	WHOLE	121.9	12	1979
60	174.3	WHOLE	140.2	23	1968
61	174.3	WHOLE	106.7	16	1975
62	174.5	PARTIAL	128.0	25	1966
63	174.5	WHOLE	146.3	15	1976
64	176.4	WHOLE	161.5	23	1968
65	176.4	WHOLE	146.3	26	1965
66	176.4	WHOLE	207.3	23	1968
67	176.7	ROTTED CORE	249.9	62	1929
68	176.7	ROTTED CORE	259.1	67	1924
69	177.2	SPLIT	365.8	27	1964
70	177.2	WHOLE	274.3	26	1965
71	179.0	WHOLE	435.9	40	1951
72	179.0	PARTIAL (SCAR)	365.8	47	1944
73	179.0	WHOLE	152.4	28	1963
74	179.0	WHOLE	182.9	18	1973
75	179.0	WHOLE	228.6	14	1977
76	179.0	WHOLE	335.3	30	1961
77	179.0	WHOLE	164.6	28	1963
78	198.0	ROTTED	304.8	57	1934
79	198.0	WHOLE	298.7	27	1964
80	198.0	WHOLE	173.7	44	1947
81	198.0	WHOLE	152.4	57	1934

Appendix 3. Dendrochronology data collected from ash (Fraxinus sp.) trees along Havasu Creek—Continued
PART 1. DATA ON DRIFTWOOD COLLECTED ALONG THE COLORADO RIVER

Sample number	[1]River mile	Condition of slab	[2]Diameter (mm)	Ring count	Year of inner ring (AD)
82	198.0	ROTTED HOLES	167.6	49	1942
83	198.0	ROTTED HOLES	201.2	77	1914
84	198.0	WHOLE	125.0	11	1980
85	198.0	BROKEN	155.4	30	1961
86	199.0	WHOLE	167.6	15	1976
87	199.0	WHOLE	320.0	28	1963
88	202.2	WHOLE	298.7	31	1960
89	204.8	BROKEN W/ SCAR	219.5	24	1967
90	204.8	BROKEN W/ SCAR	198.1	24	1967
91	205.0	SPLIT	179.8	14	1977
92	207.1	WHOLE	365.8	33	1958
93	207.1	ROTTED W/ SCAR	234.7	31	1960
93.5	207.1	WHOLE	198.1	30	1961
94	207.2	WHOLE	362.7	58	1933
95	207.2	WHOLE	204.2	40	1951
96	207.2	WHOLE	152.4	15	1976
97	207.2	WHOLE	106.7	14	1977
98	207.2	WHOLE	283.5	28	1963
99	207.2	WHOLE	207.3	57	1934
100	207.2	WHOLE	143.3	57	1934
101	207.2	WHOLE	161.5	21	1970
102	207.2	WHOLE	280.4	23	1968
103	207.2	SCAR	304.8	38	1953
104	208.7	WHOLE	170.7	15	1976
105	208.7	WHOLE	121.9	34	1957
106	208.7	WHOLE	121.9	16	1975
107	208.7	WHOLE	94.5	23	1968
108	208.7	WHOLE	173.7	22	1969
109	208.7	WHOLE	256.0	32	1959
110	208.7	WHOLE	143.3	12	1979
111	208.7	WHOLE	335.3	31	1960
112	208.9	ROTTED	204.2	68	1923
113	208.9	WHOLE	207.3	23	1968
114	208.9	WHOLE	304.8	30	1961
115	208.9	WHOLE	228.6	25	1966
116	208.9	WHOLE	149.4	20	1971
117	209.4	WHOLE	106.7	14	1977
118	209.4	SCAR	320.0	24	1967
119	209.4	WHOLE	97.5	15	1976
120	209.9	WHOLE	213.4	22	1969
121	209.9	SPLIT	317.0	26	1965
122	210.0	WHOLE	213.4	28	1963

Appendix 3. Dendrochronology data collected from ash (Fraxinus sp.) trees along Havasu Creek—Continued
PART 1. DATA ON DRIFTWOOD COLLECTED ALONG THE COLORADO RIVER

Sample number	[1]River mile	Condition of slab	[2]Diameter (mm)	Ring count	Year of inner ring (AD)
123	210.0	WHOLE	131.1	24	1967
124	210.0	WHOLE	259.1	31	1960
125	210.0	WHOLE	268.2	21	1970
126	206.0	SCAR	356.6	42	1949
126.5	206.0	WHOLE	204.2	19	1972
127	181.0	WHOLE	145.0	27	1964
128	181.0	WHOLE	115.0	26	1965
129	181.0	WHOLE	100.0	11	1980
130	181.0	WHOLE	95.0	20	1970
131	181.9	WHOLE	45.0	10	1981
132	181.9	WHOLE	120.0	12	1979
132	181.9	WHOLE	55.0	16	1975
134	181.9	WHOLE	110.0	24	1967
135	181.9	WHOLE	60.0	6	1985
136	181.9	WHOLE	85.0	17	1974
137	181.9	WHOLE	145.0	14	1977
137	181.9	WHOLE	84.0	14	1977
138	188.0	WHOLE	84.0	13	1978
139	188.0	WHOLE	100.0	15	1976
140	188.0	WHOLE	135.0	34	1957
141	188.0	WHOLE	40.0	11	1980
142	188.0	WHOLE	80.0	17	1974
143	196.0	WHOLE	110.0	14	1977
144	196.0	WHOLE	87.0	30	1961
145	179.9	WHOLE	64.0	58	1933

[1]River mile is distance along Colorado River below Lees Ferry
[2]All radial sections were taken 1 to 2 m above tree roots.

Appendix 3. Dendrochronology data collected from ash (Fraxinus sp.) trees along Havasu Creek—Continued

PART 2. SCARS ON DRIFTWOOD SAMPLES OF ASH TREES FROM HAVASU CREEK

All scars may not have been created by floods. Sample refers to sample number in Appendix 3. Repeated sample numbers indicate multiple scars.

Sample	Scar Year
7	1974
7	1976
32	1967
36	1921
65	1965
72	1982
89	1972
89	1973
89	1978
90	1973
90	1977
93	1971
93	1982
93	1987
93.5	1981
93.5	1982
102	1973
103	1983
103	1988
105	1960
107	1975
107	1982
108	1974
118	1973
118	1976
126	1982

Appendix 3. Dendrochronology data collected from ash (Fraxinus sp.) trees along Havasu Creek—Continued

PART 3. INCREMENT CORE DATA FROM VELVET ASH (*Fraxinus velutina*) TREES ALONG HAVASU CREEK

The sampling locations are shown on Figure 19. Descriptions of localities are also given below. n.d., no data was collected.

Sample number	Year of innermost ring	Diameter (mm)	Comment
Havasupai Campground Locality[1]			
MOO-01AB	1971	n.d.	germination age
MOO-02A	1946	n.d.	germination age
MOO-02BC	1974	n.d.	sprout on tipped tree
MOO-03AB	1969	n.d.	germination age
MOO-04AB	1966	n.d.	germination age
MOO-06AB	1969	n.d.	germination age
MOO-08A	1969	n.d.	germination age
MOO-09A	1971	n.d.	lost 2 mm outside rings; germination age minimum
MOO-1OAB	1979	n.d.	sprout on MOO-1 OCD
MOO-1OCD	1975	n.d.	germination age
MOO-11AB	1976	n.d.	germination age
MOO-12AB	1968	n.d.	germination age
MOO-13A	1969	n.d.	germination age
MOO-1 4AB	1970	n.d.	sprout
MOO-15AB	1966	n.d.	germination age
MOO-16A	1971	n.d.	germination age; largest ash in group
MOO-17AB	1967	n.d.	germination age; smallest ash in same group as 16A
MOO-18A	1969	n.d.	germination age
MOO-19AB	1961	n.d.	germination age
MOO-20A	1946	n.d.	germination age
Lower Mooney Falls Locality[2]			
LMO-01A	1961	230	germination age
LMO-02AB	1964	190	germination
LMO-03A	1955	190	no bark
LMO-05AB	1974	110	sprout on 5C
LMO-05C	1948	320	main branch; also tilted
LMO-06A	1948	240	germination
LMO-07A	1942	250	tree stressed; germination
LMO-08AB	1947	n.d.	base of Mooney Falls; germination
LMO-09AB	1965	n.d.	germination
LMO-1OAB	1980	n.d.	sprout on LMO-1OCD
LMO-1OCD	1963	n.d.	germination; also tilted
LMO-11AB	1948	200	
LMO-12A	1954	140	
LMO-13A	1964	130	
LMO-14A1	1945	330	
LMO-14A2	1957	330	
LMO-14B	1948	330	

Appendix 3. Dendrochronology data collected from ash (Fraxinus sp.) trees along Havasu Creek—Continued

PART 3. INCREMENT CORE DATA FROM VELVET ASH (Fraxinus velutina) TREES ALONG HAVASU CREEK

Sample number	Year of innermost ring	Diameter (mm)	Comment
Beaver Locality[3]			
BEA-01A	1945	210	dead tree; recently killed by 1990 flood?
BEA-02A	1951	280	center not reached; minimum age
BEA-03AB	1966	190	germination
BEA-04A	1968	160	double sprouted tree
BEA-05A	1972	160	germination
BEA-06A	1968	140	germination
BEA-07C	1951	n.d.	tiIted tree
BEA-07A	1975	n.d.	flood scar
BEA-08A	1933	180	germination age
BEA-09AB	1974	n.d.	scar on sprout 9CD
BEA-09CD	1962	n.d.	sprout with scar 9AB
BEA-1OAB	1950	n.d.	sprout
BEA-11AB	1929	n.d.	germination
BEA-12A	1929	n.d.	germination
Hiker Locality[4]			
HIK-01A	1918	270	can't crossdate with Grapevine samples
Grapevine Locality[5]			
GRA-01A	1929	220	outer rings very thin
GRA-02A	1905	280	rotten center
GRA-02B	1902	280	rotten center
Spring Locality[6]			
SPR-01AB	1947	220	germination
SPR-02AB	1974	n.d.	center obscure

[I] Havasupai campground locality lies on east side of Havasu Creek from directly above Mooney Falls to a point upstream and southeast of Fern Springs.
[2] Lower Mooney Falls locality lies from immediately below Mooney Falls to a point approximately 200 m downstream.
[3] Beaver locality is at the juncture of Beaver Canyon and Havasu Creek.
[4] Hiker locality is at the site of Hiker Falls. a former cascade along Havasu Creek that presently consists of dry travertine ledges. The locality consists of a single large tree on the west bank of Havasu Creek marked with a metal tag reading “Hiker Falls.”
[5] Grapevine locality lies on the west bank of Havasu Creek opposite a prominent unnamed tributary (Figure 19). The site is named for abundant “grapevines” (*Clementis* sp.) present in the area.
[6] Spring locality is located where first ash trees occur downstream of Havasu springs.

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Ashfork Winter Storms			
1	118	01/17/88	01/18/88	n.a.	146
2	114	03/10/86	03/13/86	n.a.	52
3	97	02/14/80	02/22/80	n.a.	32
4	87	12/08/65	12/19/65	n.a.	23
5	81	11/12/78	11/15/78	n.a.	18
6	75	03/01/78	03/06/78	n.a.	15
7	70	01/17/90	01/19/90	n.a.	12
8	67	02/11/27	02/17/27	n.a.	11
9	65	01/06/87	01/10/87	n.a.	10
10	65	03/21/54	03/26/54	n.a.	9
11	64	03/01/91	03/02/91	n.a.	8
12	62	12/17/78	12/20/78	n.a.	7
13	61	12/28/36	01/02/37	n.a.	7
14	60	12/03/66	12/07/66	n.a.	6
15	58	03/02/23	03/04/23	n.a.	6
16	56	01/26/57	01/30/57	n.a.	5
17	56	01/03/91	01/05/91	n.a.	5
18	56	11/29/81	11/30/81	n.a.	5
19	55	11/25/85	11/26/85	n.a.	4
20	54	03/19/91	03/23/91	n.a.	4
		Ashfork Summer Storms			
!1	151	08/12/90	08/16/90	n.a.	139
2	120	08/18/88	08/23/88	n.a.	50
3	119	07/09/19	07/18/19	n.a.	30
4	112	08/02/48	08/07/48	n.a.	22
5	107	09/23/83	09/25/83	n.a.	17
6	107	09/03/39	09/07/39	n.a.	14
7	101	08/28/51	08/29/51	n.a.	12
8	96	07/27/88	08/02/88	n.a.	10
9	95	08/25/88	08/31/88	n.a.	9
10	87	09/16/25	09/18/25	n.a.	8
11	85	09/11/69	09/14/69	n.a.	7
12	83	10/17/72	10/20/72	n.a.	7
13	80	08/15/83	08/20/83	n.a.	6
14	74	07/24/82	07/30/82	n.a.	6
15	70	07/12/81	07/18/81	n.a.	5
*16	70	08/03/54	08/06/54	n.a.	5
17	69	08/26/53	08/29/53	n.a.	5
18	69	09/20/52	09/21/52	n.a.	4
19	66	07/25/36	07/29/36	n.a.	4
20	63	07/23/64	07/27/64	n.a.	4

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Ashfork Winter Daily Precipitation			
1	91	n.a.	n.a.	01/18/88	146
2	60	n.a.	n.a.	02/28/91	52
3	55	n.a.	n.a.	01/18/90	32
4	52	n.a.	n.a.	02/19/90	23
5	50	n.a.	n.a.	12/31/15	18
6	47	n.a.	n.a.	01/04/89	15
7	44	n.a.	n.a.	11/25/85	12
8	42	n.a.	n.a.	03/01/91	11
9	42	n.a.	n.a.	03/11/86	10
10	42	n.a.	n.a.	11/30/81	9
11	42	n.a.	n.a.	11/13/78	8
12	41	n.a.	n.a.	03/02/70	7
13	40	n.a.	n.a.	11/11/85	7
14	39	n.a.	n.a.	03/23/54	6
15	39	n.a.	n.a.	03/01/78	6
16	39	n.a.	n.a.	11/29/33	5
17	37	n.a.	n.a.	02/09/93	5
18	37	n.a.	n.a.	01/27/57	5
19	37	n.a.	n.a.	01/06/89	4
20	36	n.a.	n.a.	11/12/78	4
		Ashfork Summer Daily Precipitation			
1	88	n.a.	n.a.	09/24/83	139
2	82	n.a.	n.a.	08/23/88	50
3	71	n.a.	n.a.	09/12/69	30
4	61	n.a.	n.a.	10/05/25	22
5	60	n.a.	n.a.	08/31/85	17
6	56	n.a.	n.a.	08/17/83	14
7	54	n.a.	n.a.	10/19/72	12
8	53	n.a.	n.a.	08/25/20	10
9	51	n.a.	n.a.	08/28/51	9
10	50	n.a.	n.a.	08/29/51	8
11	49	n.a.	n.a.	09/16/25	7
12	48	n.a.	n.a.	10/06/16	7
13	48	n.a.	n.a.	10/04/72	6
14	47	n.a.	n.a.	10/05/40	6
15	47	n.a.	n.a.	08/13/90	5
16	47	n.a.	n.a.	07/18/25	5
17	46	n.a.	n.a.	10/07/72	5
18	46	n.a.	n.a.	09/21/52	4
19	45	n.a.	n.a.	08/09/41	4
20	45	n.a.	n.a.	09/17/61	4

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Bright Angel Ranger Station Winter Storms			
1	186	12/29/51	01/02/52	n.a.	57
2	183	02/17/80	02/21/80	n.a.	21
3	171	03/01/78	03/06/78	n.a.	13
4	153	01/06/93	01/11/93	n.a.	9
5	137	01/15/79	01/19/79	n.a.	7
6	135	12/17/78	12/20/78	n.a.	6
7	129	03/15/58	03/17/58	n.a.	5
8	126	03/05/95	03/06/95	n.a.	4
9	126	01/07/80	01/15/80	n.a.	4
10	126	03/17/83	03/26/83	n.a.	3
11	123	01/13/93	01/19/93	n.a.	3
12	110	01/04/95	01/08/95	n.a.	3
13	108	03/20/54	03/25/54	n.a.	3
14	104	02/13/95	02/15/95	n.a.	2
15	97	01/24/57	01/30/57	n.a.	2
16	94	03/01/52	03/02/52	n.a.	2
17	94	12/25/83	12/28/83	n.a.	2
18	94	01/07/52	01/09/52	n.a.	2
19	93	02/10/92	02/14/92	n.a.	2
20	90	12/08/84	12/17/84	n.a.	2
		Bright Angel Ranger Station Summer Storms			
1	140	08/28/51	08/29/51	n.a.	81
2	84	08/01/63	08/08/63	n.a.	29
3	82	10/30/92	10/31/92	n.a.	18
4	79	10/08/60	10/11/60	n.a.	13
5	79	08/26/53	08/27/53	n.a.	10
6	70	09/20/52	09/23/52	n.a.	8
7	68	08/24/87	08/27/87	n.a.	7
8	66	07/24/83	07/28/83	n.a.	6
9	66	08/10/50	08/13/50	n.a.	5
10	65	10/14/60	10/18/60	n.a.	5
11	65	07/31/51	08/05/51	n.a.	4
12	64	10/20/79	10/21/79	n.a.	4
13	61	10/28/74	10/29/74	n.a.	4
14	60	08/16/63	08/19/63	n.a.	3
15	58	08/16/62	08/22/62	n.a.	3
16	55	09/05/81	09/10/81	n.a.	3
17	55	09/22/67	09/26/67	n.a.	3
18	54	08/30/92	09/01/92	n.a.	3
19	53	10/24/71	10/26/71	n.a.	2
20	51	09/29/83	09/30/83	n.a.	2

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Bright Angel Ranger Station Winter Daily Precipitation			
1	129	n.a.	n.a.	12/30/51	57
2	101	n.a.	n.a.	03/01/91	21
3	93	n.a.	n.a.	03/15/58	13
4	91	n.a.	n.a.	01/07/52	9
5	89	n.a.	n.a.	02/14/95	7
6	81	n.a.	n.a.	01/29/80	6
7	79	n.a.	n.a.	02/20/80	5
8	78	n.a.	n.a.	03/06/95	4
9	76	n.a.	n.a.	12/18/78	4
10	70	n.a.	n.a.	01/16/79	3
11	69	n.a.	n.a.	03/02/52	3
12	68	n.a.	n.a.	03/08/92	3
13	64	n.a.	n.a.	12/01/82	3
14	63	n.a.	n.a.	11/12/85	2
15	61	n.a.	n.a.	03/26/91	2
16	59	n.a.	n.a.	12/23/82	2
17	58	n.a.	n.a.	03/03/78	2
18	58	n.a.	n.a.	12/28/92	2
19	57	n.a.	n.a.	01/09/75	2
20	54	n.a.	n.a.	01/05/95	2
		Bright Angel Ranger Station Summer Daily Precipitation			
1	108	n.a.	n.a.	08/29/51	81
2	80	n.a.	n.a.	10/31/92	29
3	56	n.a.	n.a.	08/24/88	18
4	51	n.a.	n.a.	07/25/83	13
5	51	n.a.	n.a.	08/27/53	10
6	50	n.a.	n.a.	10/20/79	8
7	47	n.a.	n.a.	08/17/63	7
8	45	n.a.	n.a.	07/03/61	6
9	44	n.a.	n.a.	08/31/92	5
10	41	n.a.	n.a.	09/30/83	5
11	39	n.a.	n.a.	09/20/52	4
12	39	n.a.	n.a.	08/12/50	4
13	38	n.a.	n.a.	08/02/63	4
14	38	n.a.	n.a.	10/30/87	3
15	38	n.a.	n.a.	08/27/87	3
16	38	n.a.	n.a.	09/09/80	3
17	38	n.a.	n.a.	08/12/56	3
18	37	n.a.	n.a.	10/09/60	3
19	37	n.a.	n.a.	08/18/94	2
20	36	n.a.	n.a.	10/28/74	2

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Grand Canyon Winter Storms			
1	118	12/03/66	12/07/66	n.a.	157
*2	107	11/21/05	11/28/05	n.a.	56
3	104	03/01/70	03/03/70	n.a.	34
4	104	12/26/06	01/01/07	n.a.	25
5	103	12/13/08	12/17/08	n.a.	19
6	95	02/10/27	02/17/27	n.a.	16
7	94	12/01/06	12/05/06	n.a.	13
8	86	02/19/13	02/27/13	n.a.	12
9	86	11/11/78	11/12/78	n.a.	10
10	78	12/29/51	01/01/52	n.a.	9
11	75	03/01/78	03/05/78	n.a.	8
12	72	12/22/45	12/26/45	n.a.	8
!13	70	11/04/05	11/08/05	n.a.	7
14	70	11/26/19	11/27/19	n.a.	6
!15	68	01/06/93	01/11/93	n.a.	6
16	68	12/17/78	12/20/78	n.a.	6
17	66	11/21/06	11/27/06	n.a.	5
18	65	12/26/36	01/02/37	n.a.	5
19	64	02/17/80	02/21/80	n.a.	5
20	61	01/07/40	01/13/40	n.a.	4
		Grand Canyon Summer Storms			
1	140	09/04/39	09/08/39	n.a.	158
2	115	10/02/07	10/06/07	n.a.	57
3	113	09/02/07	09/05/07	n.a.	34
4	91	08/17/89	08/19/89	n.a.	25
5	89	07/30/04	07/31/04	n.a.	19
6	86	07/23/83	07/25/83	n.a.	16
7	81	10/15/72	10/21/72	n.a.	13
8	76	08/25/04	08/31/04	n.a.	12
9	74	10/01/12	10/05/12	n.a.	10
10	73	09/10/39	09/13/39	n.a.	9
11	72	09/28/37	09/29/37	n.a.	8
12	69	08/18/84	08/22/84	n.a.	8
13	68	08/28/51	08/29/51	n.a.	7
14	67	09/05/81	09/08/81	n.a.	7
15	66	08/21/07	08/24/07	n.a.	6
16	65	09/16/25	09/19/25	n.a.	6
17	65	08/26/53	08/28/53	n.a.	5
18	64	09/26/11	09/30/11	n.a.	5
19	64	07/20/68	07/28/68	n.a.	5
20	64	07/23/04	07/26/04	n.a.	5

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Grand Canyon Winter Daily Precipitation			
1	101	n.a.	n.a.	03/01/70	157
2	50	n.a.	n.a.	11/11/78	56
3	48	n.a.	n.a.	12/27/23	34
4	45	n.a.	n.a.	02/29/60	25
5	44	n.a.	n.a.	11/26/19	19
6	43	n.a.	n.a.	12/05/66	16
7	42	n.a.	n.a.	12/30/51	13
8	41	n.a.	n.a.	12/18/78	12
9	39	n.a.	n.a.	12/22/45	10
10	38	n.a.	n.a.	12/06/24	9
11	38	n.a.	n.a.	01/17/14	8
12	38	n.a.	n.a.	11/20/13	8
13	37	n.a.	n.a.	03/06/95	7
14	37	n.a.	n.a.	11/12/78	6
15	36	n.a.	n.a.	12/25/42	6
16	36	n.a.	n.a.	02/19/90	6
17	36	n.a.	n.a.	03/14/44	5
18	36	n.a.	n.a.	11/21/05	5
*19	34	n.a.	n.a.	02/20/93	5
20	34	n.a.	n.a.	01/31/22	4
		Grand Canyon Summer Daily Precipitation			
1	80	n.a.	n.a.	07/25/83	157
2	69	n.a.	n.a.	09/29/37	57
3	59	n.a.	n.a.	09/06/81	34
4	56	n.a.	n.a.	08/29/51	25
5	51	n.a.	n.a.	10/06/16	19
6	51	n.a.	n.a.	09/03/07	16
7	51	n.a.	n.a.	07/30/04	13
8	49	n.a.	n.a.	09/17/25	12
9	48	n.a.	n.a.	09/04/07	10
10	46	n.a.	n.a.	10/31/51	9
11	46	n.a.	n.a.	08/19/89	8
12	43	n.a.	n.a.	08/22/92	8
13	42	n.a.	n.a.	08/03/74	7
14	42	n.a.	n.a.	09/05/39	7
15	41	n.a.	n.a.	07/18/50	6
16	41	n.a.	n.a.	08/25/40	6
17	40	n.a.	n.a.	10/04/11	5
18	39	n.a.	n.a.	07/25/74	5
19	38	n.a.	n.a.	10/06/24	5
20	38	n.a.	n.a.	07/31/04	5

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Mount Trumbull Winter Storms			
1	94	12/19/21	12/25/21	n.a.	94
2	71	02/11/27	02/17/27	n.a.	34
3	57	12/06/66	12/07/66	n.a.	21
4	56	11/12/46	11/15/46	n.a.	15
*5	55	02/08/20	02/11/20	n.a.	12
6	52	12/27/36	12/29/36	n.a.	9
7	52	02/08/32	02/10/32	n.a.	8
8	47	03/01/38	03/05/38	n.a.	7
9	44	02/03/28	02/05/28	n.a.	6
10	42	02/17/71	02/18/71	n.a.	5
11	40	12/04/26	12/08/26	n.a.	5
12	39	03/09/43	03/11/43	n.a.	5
13	39	03/21/54	03/25/54	n.a.	4
14	38	12/09/65	12/13/65	n.a.	4
15	36	02/11/36	02/16/36	n.a.	4
16	36	12/04/47	12/08/47	n.a.	3
17	32	02/13/54	02/14/54	n.a.	3
18	32	12/29/51	12/31/51	n.a.	3
19	32	12/23/40	12/25/40	n.a.	3
20	31	02/09/76	02/10/76	n.a.	3
		Mount Trumbull Summer Storms			
*1	112	07/24/55	07/25/55	n.a.	93
2	98	09/10/39	09/12/39	n.a.	33
3	94	09/04/39	09/06/39	n.a.	20
4	88	10/04/25	10/06/25	n.a.	15
5	66	07/29/76	07/30/76	n.a.	11
6	66	08/23/61	08/24/61	n.a.	9
7	62	07/25/39	07/28/39	n.a.	8
8	60	08/05/41	08/06/41	n.a.	7
9	57	08/03/48	08/06/48	n.a.	6
10	56	08/08/30	08/11/30	n.a.	5
11	55	08/11/50	08/12/50	n.a.	5
12	54	08/22/49	08/23/49	n.a.	4
13	51	10/26/74	10/28/74	n.a.	4
14	50	07/23/41	07/24/41	n.a.	4
15	50	07/26/26	07/28/26	n.a.	4
16	49	10/15/72	10/22/72	n.a.	3
*17	48	08/13/35	08/15/35	n.a.	3
18	48	07/23/67	07/24/67	n.a.	3
19	47	09/16/40	09/17/40	n.a.	3
20	47	10/06/33	10/11/33	n.a.	3

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Mount Trumbull Winter Daily Precipitation			
1	38	n.a.	n.a.	12/31/71	94
2	38	n.a.	n.a.	12/06/66	34
3	37	n.a.	n.a.	03/03/38	20
4	36	n.a.	n.a.	12/28/36	15
5	34	n.a.	n.a.	01/27/49	11
6	33	n.a.	n.a.	01/20/21	9
7	32	n.a.	n.a.	11/13/57	8
8	30	n.a.	n.a.	12/27/46	7
9	28	n.a.	n.a.	12/30/51	6
10	28	n.a.	n.a.	12/20/21	5
11	28	n.a.	n.a.	03/10/43	5
12	27	n.a.	n.a.	03/31/69	5
13	27	n.a.	n.a.	12/09/65	4
14	27	n.a.	n.a.	11/13/46	4
15	26	n.a.	n.a.	02/14/54	4
!16	26	n.a.	n.a.	02/10/20	3
17	26	n.a.	n.a.	02/04/28	3
18	25	n.a.	n.a.	02/05/48	3
19	25	n.a.	n.a.	02/16/27	3
20	25	n.a.	n.a.	12/19/21	3
		Mount Trumbull Summer Daily Precipitation			
*1	111	n.a.	n.a.	07/24/55	93
2	73	n.a.	n.a.	09/18/20	33
3	62	n.a.	n.a.	07/29/76	20
4	52	n.a.	n.a.	09/06/39	15
5	51	n.a.	n.a.	08/24/61	11
6	49	n.a.	n.a.	07/23/41	9
7	47	n.a.	n.a.	08/29/51	8
8	47	n.a.	n.a.	09/12/39	7
9	47	n.a.	n.a.	08/12/50	6
10	45	n.a.	n.a.	08/01/43	5
11	45	n.a.	n.a.	09/17/40	5
12	44	n.a.	n.a.	08/23/49	4
13	44	n.a.	n.a.	10/10/60	4
14	43	n.a.	n.a.	09/06/69	4
15	43	n.a.	n.a.	07/26/26	4
16	42	n.a.	n.a.	10/05/25	3
17	42	n.a.	n.a.	08/18/20	3
18	42	n.a.	n.a.	09/11/39	3
19	40	n.a.	n.a.	10/04/25	3
20	39	n.a.	n.a.	10/01/21	3

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Phantom Ranch Winter Storms			
1	75	n.a.	11/11/78	11/12/78	55
2	64	n.a.	01/18/80	01/19/80	20
3	53	n.a.	12/03/66	12/07/66	12
!4	52	n.a.	01/06/93	01/11/93	9
5	50	n.a.	02/17/80	02/21/80	7
6	46	n.a.	12/17/78	12/19/78	6
7	39	n.a.	01/04/95	01/08/95	5
8	38	n.a.	03/26/91	03/28/91	4
9	38	n.a.	03/01/95	03/06/95	4
10	36	n.a.	03/01/78	03/05/78	3
11	36	n.a.	11/27/81	11/30/81	3
*12	34	n.a.	02/19/93	02/21/93	3
13	33	n.a.	11/25/85	11/30/85	2
14	31	n.a.	01/09/80	01/11/80	2
!15	31	n.a.	01/13/93	01/20/93	2
16	31	n.a.	12/05/94	12/07/94	2
17	30	n.a.	02/02/88	02/03/88	2
18	29	n.a.	03/17/83	03/21/83	2
19	28	n.a.	12/28/92	12/30/92	2
20	27	n.a.	12/04/72	12/05/72	2
		Phantom Ranch Summer Storms			
1	62	n.a.	08/18/84	08/23/84	53
2	62	n.a.	07/21/83	07/26/83	19
3	43	n.a.	10/15/72	10/19/72	12
4	40	n.a.	08/16/89	08/20/89	8
5	39	n.a.	09/06/81	09/08/81	6
6	39	n.a.	08/10/81	08/11/81	5
7	38	n.a.	10/14/94	10/17/94	5
8	38	n.a.	09/07/75	09/13/75	4
9	37	n.a.	09/23/76	09/27/76	3
10	35	n.a.	08/23/82	08/26/82	3
11	35	n.a.	07/16/76	07/18/76	3
12	34	n.a.	09/06/67	09/07/67	3
!13	33	n.a.	08/13/90	08/16/90	2
14	33	n.a.	09/11/69	09/12/69	2
15	32	n.a.	10/20/79	10/21/79	2
16	30	n.a.	08/18/93	08/21/93	2
17	27	n.a.	10/03/72	10/04/72	2
18	27	n.a.	09/09/80	09/10/80	2
19	26	n.a.	10/02/81	10/05/81	2
20	25	n.a.	08/21/92	08/23/92	2

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Phantom Ranch Winter Daily Precipitation			
1	47	n.a.	n.a.	11/11/78	55
2	35	n.a.	n.a.	12/18/78	20
3	33	n.a.	n.a.	02/19/80	12
4	33	n.a.	n.a.	01/18/80	9
5	33	n.a.	n.a.	02/19/90	7
6	30	n.a.	n.a.	01/19/80	6
7	28	n.a.	n.a.	11/12/78	5
8	26	n.a.	n.a.	12/04/66	4
9	25	n.a.	n.a.	03/26/91	4
10	25	n.a.	n.a.	01/05/95	3
11	24	n.a.	n.a.	12/28/92	3
12	24	n.a.	n.a.	02/02/88	3
13	24	n.a.	n.a.	02/15/86	2
14	23	n.a.	n.a.	03/01/91	2
15	23	n.a.	n.a.	11/12/85	2
16	22	n.a.	n.a.	03/18/83	2
17	22	n.a.	n.a.	02/20/93	2
18	22	n.a.	n.a.	11/30/82	2
19	21	n.a.	n.a.	01/08/93	2
20	21	n.a.	n.a.	12/31/91	2
		Phantom Ranch Summer Daily Precipitation			
1	47	n.a.	n.a.	07/25/83	53
2	43	n.a.	n.a.	09/01/85	19
3	33	n.a.	n.a.	09/06/67	12
4	33	n.a.	n.a.	09/12/69	8
5	32	n.a.	n.a.	10/15/94	6
6	32	n.a.	n.a.	08/18/84	5
7	26	n.a.	n.a.	10/05/66	4
8	25	n.a.	n.a.	08/20/93	4
9	25	n.a.	n.a.	09/09/80	3
10	23	n.a.	n.a.	08/11/81	3
11	23	n.a.	n.a.	09/06/81	3
12	23	n.a.	n.a.	08/19/89	3
13	22	n.a.	n.a.	08/20/84	2
14	22	n.a.	n.a.	10/06/93	2
15	22	n.a.	n.a.	10/04/72	2
16	21	n.a.	n.a.	10/02/81	2
17	21	n.a.	n.a.	09/08/75	2
18	20	n.a.	n.a.	10/11/86	2
19	19	n.a.	n.a.	09/25/67	2
20	19	n.a.	n.a.	08/25/82	2

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Seligman Winter Storms			
1	99	12/13/67	12/16/67	n.a.	151
2	72	03/07/68	03/09/68	n.a.	54
3	69	02/14/80	02/22/80	n.a.	33
4	69	02/23/44	02/29/44	n.a.	24
5	64	11/11/78	11/12/78	n.a.	19
!6	64	11/05/05	11/06/05	n.a.	15
7	59	03/01/70	03/02/70	n.a.	13
8	57	03/01/78	03/06/78	n.a.	11
!9	54	02/08/93	02/10/93	n.a.	10
10	49	01/23/49	01/26/49	n.a.	9
11	47	02/15/27	02/17/27	n.a.	8
12	47	12/20/21	12/23/21	n.a.	7
13	46	02/02/08	02/04/08	n.a.	7
14	45	03/01/91	03/02/91	n.a.	6
15	45	03/22/54	03/25/54	n.a.	6
16	45	01/13/93	01/17/93	n.a.	5
17	44	12/09/65	12/10/65	n.a.	5
18	43	12/17/78	12/20/78	n.a.	5
19	42	12/05/66	12/07/66	n.a.	5
20	42	01/23/44	01/27/44	n.a.	4
		Seligman Summer Storms			
1	146	07/19/70	07/22/70	n.a.	147
2	112	09/03/39	09/06/39	n.a.	53
3	94	07/22/15	07/25/15	n.a.	32
4	91	08/28/51	08/29/51	n.a.	23
5	86	10/01/21	10/02/21	n.a.	18
*6	86	08/20/21	08/21/21	n.a.	15
7	85	09/23/83	09/24/83	n.a.	13
8	75	10/04/25	10/05/25	n.a.	11
9	74	09/05/24	09/10/24	n.a.	10
10	72	07/31/64	08/01/64	n.a.	9
!11	71	08/06/21	08/07/21	n.a.	8
12	69	08/23/55	08/25/55	n.a.	7
13	68	08/03/39	08/04/39	n.a.	7
14	67	07/07/19	07/13/19	n.a.	6
15	64	08/19/94	08/21/94	n.a.	6
16	64	09/18/90	09/23/90	n.a.	5
17	64	09/04/07	09/05/07	n.a.	5
18	56	07/11/14	07/15/14	n.a.	5
19	55	09/12/39	09/13/39	n.a.	4
20	55	08/10/81	08/15/81	n.a.	4

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Seligman Winter Daily Precipitation			
1	71	n.a.	n.a.	03/07/68	151
!2	55	n.a.	n.a.	11/05/05	54
3	48	n.a.	n.a.	11/11/78	33
4	47	n.a.	n.a.	03/01/70	24
5	44	n.a.	n.a.	12/31/15	19
6	38	n.a.	n.a.	11/27/19	15
7	38	n.a.	n.a.	02/23/43	13
8	38	n.a.	n.a.	03/27/25	11
9	38	n.a.	n.a.	01/18/16	10
!10	37	n.a.	n.a.	02/07/20	9
11	36	n.a.	n.a.	12/16/67	8
12	35	n.a.	n.a.	12/03/08	7
13	34	n.a.	n.a.	12/10/65	7
*14	33	n.a.	n.a.	02/22/20	6
15	33	n.a.	n.a.	11/07/63	6
16	32	n.a.	n.a.	03/01/78	5
17	32	n.a.	n.a.	12/21/67	5
18	31	n.a.	n.a.	12/26/21	5
19	31	n.a.	n.a.	03/12/18	5
20	30	n.a.	n.a.	12/15/67	4
		Seligman Summer Daily Precipitation			
1	123	n.a.	n.a.	07/21/70	147
2	69	n.a.	n.a.	10/05/25	53
3	60	n.a.	n.a.	09/23/83	32
4	58	n.a.	n.a.	10/02/21	23
*5	56	n.a.	n.a.	08/21/21	18
6	56	n.a.	n.a.	08/20/94	15
7	52	n.a.	n.a.	08/28/51	13
8	51	n.a.	n.a.	10/06/16	11
9	50	n.a.	n.a.	08/03/39	10
10	48	n.a.	n.a.	07/16/30	9
11	48	n.a.	n.a.	07/15/86	8
12	47	n.a.	n.a.	08/23/55	7
!13	46	n.a.	n.a.	08/07/21	7
14	45	n.a.	n.a.	07/31/64	6
15	44	n.a.	n.a.	09/25/19	6
16	43	n.a.	n.a.	09/12/39	5
17	41	n.a.	n.a.	08/31/09	5
18	39	n.a.	n.a.	07/25/39	5
19	39	n.a.	n.a.	08/19/06	4
20	39	n.a.	n.a.	09/04/39	4

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Supai Winter Storms			
1	40	12/03/66	12/07/66	n.a.	55
2	33	11/14/78	11/15/78	n.a.	20
3	33	11/04/59	11/05/59	n.a.	12
4	32	03/01/70	03/03/70	n.a.	9
5	29	02/06/65	02/07/65	n.a.	7
6	28	12/09/65	12/15/65	n.a.	6
7	27	12/17/78	12/19/78	n.a.	5
8	25	12/27/84	12/29/84	n.a.	4
9	25	02/07/66	02/08/66	n.a.	4
10	25	11/27/81	11/29/81	n.a.	3
11	25	11/06/81	11/07/81	n.a.	3
12	23	11/01/74	11/03/74	n.a.	3
13	22	01/09/80	01/15/80	n.a.	2
14	22	03/01/78	03/03/78	n.a.	2
15	22	03/21/83	03/25/83	n.a.	2
16	22	01/10/78	01/11/78	n.a.	2
17	21	12/04/72	12/05/72	n.a.	2
18	21	03/26/73	03/29/73	n.a.	2
19	21	03/17/83	03/19/83	n.a.	2
20	20	02/19/71	02/20/71	n.a.	2
		Supai Summer Storms			
1	67	08/09/81	08/14/81	n.a.	55
*2	53	07/21/70	07/23/70	n.a.	20
3	47	09/21/67	09/25/67	n.a.	12
4	44	07/18/84	07/21/84	n.a.	9
5	41	08/21/60	08/22/60	n.a.	7
6	40	08/19/57	08/12/59	n.a.	5
8	34	10/17/72	10/20/72	n.a.	4
*9	32	07/08/70	07/10/70	n.a.	4
10	31	07/30/56	07/31/56	n.a.	3
11	31	10/09/86	10/12/86	n.a.	3
12	30	10/20/79	10/21/79	n.a.	3
13	29	08/05/79	08/06/79	n.a.	2
14	29	08/14/58	08/16/58	n.a.	2
15	28	07/23/83	07/25/83	n.a.	2
16	28	09/04/58	09/08/58	n.a.	2
17	27	07/31/68	08/01/68	n.a.	2
18	27	10/01/81	10/03/81	n.a.	2
19	26	09/25/76	09/26/76	n.a.	2
20	26	08/02/64	08/06/64	n.a.	2

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Supai Winter Daily Precipitation			
1	41	n.a.	n.a.	12/19/67	55
2	40	n.a.	n.a.	12/06/86	20
3	34	n.a.	n.a.	11/07/63	12
4	28	n.a.	n.a.	12/27/79	9
5	26	n.a.	n.a.	11/12/85	7
6	25	n.a.	n.a.	03/22/58	6
7	24	n.a.	n.a.	11/07/81	5
8	23	n.a.	n.a.	02/14/87	4
9	23	n.a.	n.a.	12/27/84	4
10	22	n.a.	n.a.	03/01/70	3
11	20	n.a.	n.a.	11/14/78	3
12	19	n.a.	n.a.	02/06/65	3
13	18	n.a.	n.a.	02/08/66	2
14	18	n.a.	n.a.	11/05/59	2
15	17	n.a.	n.a.	12/05/72	2
16	17	n.a.	n.a.	02/04/58	2
17	17	n.a.	n.a.	11/02/74	2
18	17	n.a.	n.a.	03/18/83	2
19	16	n.a.	n.a.	02/09/76	2
20	16	n.a.	n.a.	12/02/78	2
		Supai Summer Daily Precipitation			
1	60	n.a.	n.a.	07/30/76	55
2	40	n.a.	n.a.	08/21/60	20
3	37	n.a.	n.a.	08/11/59	12
4	36	n.a.	n.a.	08/18/69	9
5	34	n.a.	n.a.	08/10/81	7
6	32	n.a.	n.a.	07/04/75	6
7	31	n.a.	n.a.	07/29/69	5
8	29	n.a.	n.a.	09/13/64	4
9	28	n.a.	n.a.	08/05/79	4
10	27	n.a.	n.a.	08/20/57	3
11	27	n.a.	n.a.	10/31/57	3
12	27	n.a.	n.a.	10/20/79	3
13	25	n.a.	n.a.	07/11/85	2
*14	25	n.a.	n.a.	07/21/70	2
15	25	n.a.	n.a.	07/27/56	2
16	24	n.a.	n.a.	08/14/80	2
17	23	n.a.	n.a.	09/24/67	2
18	23	n.a.	n.a.	10/11/86	2
19	22	n.a.	n.a.	09/06/81	2
20	22	n.a.	n.a.	08/24/80	2

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Tuweep Ranger Station Winter Storms			
1	157	12/06/66	12/07/66	n.a.	63
2	97	12/12/65	12/13/65	n.a.	22
3	65	12/29/51	12/31/51	n.a.	14
4	48	03/21/54	03/25/54	n.a.	10
5	48	02/20/80	02/21/80	n.a.	8
6	45	03/05/78	03/06/78	n.a.	6
7	37	03/09/75	03/11/75	n.a.	5
8	36	11/11/85	11/13/85	n.a.	5
9	35	03/01/78	03/03/78	n.a.	4
10	31	03/19/79	03/22/79	n.a.	4
11	31	11/06/77	11/07/77	n.a.	3
12	31	01/25/54	01/26/54	n.a.	3
13	30	12/27/84	12/28/84	n.a.	3
14	30	02/09/76	02/10/76	n.a.	3
15	29	11/27/81	11/28/81	n.a.	2
16	29	02/14/54	02/15/54	n.a.	2
17	28	02/17/80	02/18/80	n.a.	2
18	28	03/01/52	03/02/52	n.a.	2
19	27	01/29/80	01/30/80	n.a.	2
20	27	11/11/78	11/12/78	n.a.	2
		Tuweep Ranger Station Summer Storms			
1	104	08/23/82	08/26/82	n.a.	67
2	91	07/18/84	07/23/84	n.a.	24
3	73	08/03/48	08/04/48	n.a.	15
4	73	07/18/69	07/19/69	n.a.	11
5	54	07/14/53	07/18/53	n.a.	8
6	51	08/01/51	08/03/51	n.a.	7
7	47	09/25/76	09/27/76	n.a.	6
8	47	07/20/70	07/25/70	n.a.	5
9	46	07/31/68	08/01/68	n.a.	4
10	46	08/19/70	08/20/70	n.a.	4
11	39	07/24/83	07/25/83	n.a.	4
12	39	08/19/57	08/21/57	n.a.	3
13	36	09/20/52	09/21/52	n.a.	3
14	35	08/11/79	08/13/79	n.a.	3
15	35	08/29/61	08/30/61	n.a.	3
16	34	09/11/69	09/13/69	n.a.	2
17	33	10/20/57	10/21/57	n.a.	2
18	33	08/14/67	08/18/67	n.a.	2
19	33	07/16/59	07/18/59	n.a.	2
20	32	07/24/76	07/25/76	n.a.	2

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Tuweep Ranger Station Winter Daily Precipitation			
1	96	n.a.	n.a.	12/06/66	62
2	88	n.a.	n.a.	12/12/65	22
3	61	n.a.	n.a.	12/07/66	14
4	55	n.a.	n.a.	12/30/51	10
5	51	n.a.	n.a.	12/19/78	8
6	46	n.a.	n.a.	12/31/72	6
7	43	n.a.	n.a.	01/25/69	5
8	38	n.a.	n.a.	03/05/78	5
9	36	n.a.	n.a.	02/20/80	4
10	34	n.a.	n.a.	03/02/70	4
11	34	n.a.	n.a.	01/26/56	3
12	32	n.a.	n.a.	03/22/58	3
13	30	n.a.	n.a.	03/24/64	3
14	30	n.a.	n.a.	01/19/80	3
15	30	n.a.	n.a.	02/06/76	2
16	28	n.a.	n.a.	02/09/76	2
17	28	n.a.	n.a.	03/25/50	2
18	27	n.a.	n.a.	11/06/60	2
19	27	n.a.	n.a.	11/02/74	2
20	27	n.a.	n.a.	01/25/54	2
		Tuweep Ranger Station Summer Daily Precipitation			
1	67	n.a.	n.a.	07/19/69	67
2	62	n.a.	n.a.	08/29/51	24
3	58	n.a.	n.a.	09/24/67	15
4	53	n.a.	n.a.	07/20/84	10
5	46	n.a.	n.a.	08/23/82	8
6	46	n.a.	n.a.	08/03/48	7
7	44	n.a.	n.a.	08/26/82	6
8	42	n.a.	n.a.	07/18/50	5
9	39	n.a.	n.a.	09/24/58	4
10	39	n.a.	n.a.	08/10/81	4
11	38	n.a.	n.a.	10/02/81	4
12	38	n.a.	n.a.	08/19/70	3
13	38	n.a.	n.a.	07/25/83	3
14	37	n.a.	n.a.	07/31/68	3
15	36	n.a.	n.a.	10/20/79	3
16	36	n.a.	n.a.	09/25/76	2
17	36	n.a.	n.a.	08/26/53	2
18	35	n.a.	n.a.	10/31/57	2
19	34	n.a.	n.a.	08/25/55	2
20	32	n.a.	n.a.	07/18/61	2

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Williams Winter Storms			
1	183	02/13/80	02/22/80	n.a.	159
*2	147	02/19/93	02/21/93	n.a.	57
3	145	11/22/65	11/26/65	n.a.	35
4	136	12/27/36	01/01/37	n.a.	25
5	134	02/11/27	02/16/27	n.a.	19
6	132	12/03/66	12/07/66	n.a.	16
7	130	02/04/76	02/10/76	n.a.	14
8	121	12/08/65	12/17/65	n.a.	12
*9	120	02/19/20	02/22/20	n.a.	10
10	119	01/16/17	01/22/17	n.a.	9
11	110	03/11/18	03/13/18	n.a.	8
12	107	01/16/16	01/20/16	n.a.	8
13	106	02/17/17	02/19/17	n.a.	7
14	105	12/29/51	01/01/52	n.a.	7
15	103	02/07/32	02/11/32	n.a.	6
16	101	11/01/57	11/04/57	n.a.	6
17	100	02/01/05	02/06/05	n.a.	5
18	99	01/09/05	01/12/05	n.a.	5
19	99	01/10/30	01/13/30	n.a.	5
20	98	12/14/08	12/17/08	n.a.	5
		Williams Summer Storms			
1	193	07/08/19	07/24/19	n.a.	160
2	143	10/15/72	10/21/72	n.a.	58
3	142	09/04/39	09/07/39	n.a.	35
4	123	10/01/16	10/06/16	n.a.	25
5	123	07/22/76	07/30/76	n.a.	20
6	110	08/07/46	08/12/46	n.a.	16
7	103	07/23/68	08/01/68	n.a.	14
8	101	07/13/55	07/21/55	n.a.	12
*9	100	07/31/92	08/06/92	n.a.	10
10	99	08/28/51	08/29/51	n.a.	9
11	98	09/22/83	09/24/83	n.a.	8
12	96	08/08/43	08/15/43	n.a.	8
13	92	09/17/65	09/20/65	n.a.	7
14	92	10/08/60	10/11/60	n.a.	7
15	84	07/27/89	07/31/89	n.a.	6
16	82	08/04/71	08/06/71	n.a.	6
17	82	08/25/53	08/29/53	n.a.	5
18	81	08/02/48	08/08/48	n.a.	5
19	80	07/25/29	08/06/29	n.a.	5
20	80	09/13/41	09/15/41	n.a.	5

Appendix 4. Rankings and estimated probabilities for the 20 largest multiday storms and daily precipitation events at nine stations in northern Arizona—Continued

Rank	Precipitation (mm)	STORM DATES From	To	Date of Highest Daily Total	Recurrence Interval (yrs)
		Williams Winter Daily Precipitation			
*1	89	n.a.	n.a.	02/20/93	158
2	84	n.a.	n.a.	02/19/18	57
3	75	n.a.	n.a.	12/30/51	35
4	70	n.a.	n.a.	11/03/57	25
5	70	n.a.	n.a.	02/19/17	19
6	70	n.a.	n.a.	02/09/32	16
7	69	n.a.	n.a.	02/09/76	14
8	66	n.a.	n.a.	01/11/30	12
9	64	n.a.	n.a.	12/28/92	10
10	63	n.a.	n.a.	11/25/65	9
11	63	n.a.	n.a.	03/08/18	8
12	62	n.a.	n.a.	11/23/65	8
13	62	n.a.	n.a.	12/16/08	7
14	61	n.a.	n.a.	12/26/23	7
15	59	n.a.	n.a.	03/13/18	6
16	58	n.a.	n.a.	11/01/87	6
*17	56	n.a.	n.a.	02/19/93	5
18	56	n.a.	n.a.	01/01/10	5
19	56	n.a.	n.a.	02/14/80	5
20	56	n.a.	n.a.	12/31/15	5
		Williams Summer Daily Precipitation			
1	69	n.a.	n.a.	09/18/65	160
2	63	n.a.	n.a.	08/29/51	57
3	58	n.a.	n.a.	10/06/93	35
4	58	n.a.	n.a.	09/23/83	25
5	57	n.a.	n.a.	07/01/80	20
*6	56	n.a.	n.a.	07/18/35	16
7	56	n.a.	n.a.	10/19/72	14
8	54	n.a.	n.a.	09/05/39	12
9	52	n.a.	n.a.	10/04/40	10
10	52	n.a.	n.a.	08/04/63	9
11	51	n.a.	n.a.	07/08/19	8
12	51	n.a.	n.a.	07/31/92	8
13	51	n.a.	n.a.	08/04/71	7
14	51	n.a.	n.a.	07/18/46	7
15	50	n.a.	n.a.	10/06/24	6
16	50	n.a.	n.a.	07/20/16	6
17	49	n.a.	n.a.	10/18/72	5
18	49	n.a.	n.a.	10/05/25	5
19	49	n.a.	n.a.	09/18/63	5
20	49	n.a.	n.a.	08/10/46	5

* indicates a Havasu Creek flood;!, indicates that the storm occurred in a month before a Havasu Creek flood; n.a., not applicable.